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PHD THESIS

Squeak and Rattle Prediction for Robust Product Development

In the automotive industry

MOHSEN BAYANI

DEPARTMENT OF INDUSTRIAL AND MATERIALS SCIENCE
CHALMERS UNIVERSITY OF TECHNOLOGY
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MOHSEN BAYANI
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Department of Industrial and Materials Science
Chalmers University of Technology
SE-412 96 Gothenburg
Sweden
Telephone + 46 (0)31-772 1000

mohsen.bayani@chalmers.se
mohsen.bayani@volvocars.com

Cover:
The cover illustration is a word cloud representation of the most frequently used words and terms in the thesis text. The image emphasises the studied phenomena, squeak and rattle (S&R), in the automotive context.

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To my family

Squeak and Rattle Prediction for Robust Product Development
MOHSEN BAYANI
Department of Industrial and Materials Science
Chalmers University of Technology

ABSTRACT

Squeak and rattle are nonstationary, irregular, and impulsive sounds that are audible inside the car cabin. For decades, customer complaints about squeak and rattle have been, and still are, among the top quality issues in the automotive industry. These annoying sounds are perceived as quality defect indications and burden warranty costs to the car manufacturers. Today, the quality improvements regarding the persistent type of sounds in the car, as well as the increasing popularity of electric engines, as green and quiet propulsion solutions, stress the necessity for attenuating annoying sounds like squeak and rattle more than in the past. The economical and robust solutions to this problem are to be sought in the pre-design-freeze phases of the product development and by employing design-concept-related practices. To achieve this goal, prediction and evaluation tools and methods are required to deal with the squeak and rattle quality issues upfront in the product development process.

The available tools and methods for the prediction of squeak and rattle sounds in the pre-design-freeze phases of a car development process are not yet sufficiently mature. The complexity of the squeak and rattle events, the existing knowledge gap about the mechanisms behind the squeak and rattle sounds, the lack of accurate simulation and post-processing methods, as well as the computational cost of complex simulations are some of the significant hurdles in this immaturity. This research addresses this problem by identifying a framework for the prediction of squeak and rattle sounds based on a cause-and-effect diagram. The main domains and the elements and the sub-contributors to the problem in each domain within this framework are determined through literature studies, field explorations and descriptive studies conducted on the subject. Further, improvement suggestions for the squeak and rattle evaluation and prediction methods are proposed through prescriptive studies. The applications of some of the proposed methods in the automotive industry are demonstrated and examined in industrial problems.

The outcome of this study enhances the understanding of some of the parameters engaged in the squeak and rattle generation. Simulation methods are proposed to actively involve the contributing factors studied in this work for squeak and rattle risk evaluation. To enhance the efficiency and accuracy of the risk evaluation process, methods were investigated and proposed for the system excitation efficiency, modelling accuracy and efficiency and quantification of the response in the time and frequency domains. The demonstrated simulation methods besides the improved understanding of the mechanisms behind the phenomenon can facilitate a more accurate and robust prediction of squeak and rattle risk during the pre-design-freeze stages of the car development.

Keywords: squeak and rattle, simulation, product development, structural dynamics, finite element analysis, sound quality.

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Gothenburg, June 2021

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Paper I (study 1)

M. Bayani, A. Nasseri, V. Heszler, C. Wickman, and R. Söderberg, "Empirical characterisation of friction parameters for non-linear stick-slip simulation to predict the severity of squeak sounds," in *SAE International Journal of Vehicle Dynamics, Stability and NVH*, 2022, vol. 6, no. 1, doi: 10.4271/10-06-01-0004.

Distribution of work: Bayani initiated the idea, post-processed and analysed the results, authored the paper and actively supervised the empirical data collections and virtual simulation activities. Nasseri and Heszler conducted the empirical and virtual data collection and analysed and post-processed the data. Wickman and Söderberg contributed as reviewers.

Paper II (study 2)

M. Bayani, A. Basheer, F. Godborg, R. Söderberg, and C. Wickman, "Finite Element Model Reduction Applied to Nonlinear Impact Simulation for Squeak and Rattle Prediction," in *SAE International Journal of Advances and Current Practices in Mobility*, 2020, vol. 3, no. 2, pp. 1081–1091. doi: 10.4271/2020-01-1558.

Distribution of work: Bayani initiated and developed the idea, collected the experimental data and authored the paper. Basheer and Godborg prepared the models and ran the simulations. Bayani, Basheer and Godborg collected the simulation data and analysed the data. Wickman and Söderberg contributed as reviewers.

Paper III (study 3)

M. Bayani, J. Nilsson, R. Blom, C. Wickman, and R. Söderberg, "A strategy for developing an inclusive load case for verification of squeak and rattle noises in the car cabin," in *SAE Noise and Vibration Conference & Exhibition*, Grand Rapids and online, USA, 7 Sep. 2021. doi: 10.4271/2021-01-1088.

Distribution of work: Bayani initiated and developed the idea, the theory and methods, planned the activities, authored the paper and actively supervised and participated in empirical and virtual data collection and analysis and method development. Nilsson and Blom collected the empirical and virtual data, wrote the scripts, and analysed and post-processed the data. Wickman and Söderberg contributed as reviewers.

Paper IV (study 4)

M. Bayani, C. Wickman, A. D. Krishnaswamy, C. Sathappan, and R. Söderberg, "Resonance Risk and Mode Shape Management in the Frequency Domain to Prevent Squeak and Rattle," *Journal of Vibration and Acoustics*, vol. 144, no. 1, pp. 13, Feb. 2022, American Society of Mechanical Engineers (ASME), doi: 10.1115/1.4051411.

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Paper V (study 5)

M. Bayani, C. Wickman, L. Lindkvist, and R. Söderberg, "Squeak and rattle prevention by geometric variation management using a two-stage evolutionary optimisation approach," *Journal of Computing and Information Science in Engineering*, vol. 22, no. 1, pp. 16, Feb. 2022, American Society of Mechanical Engineers (ASME), doi: 10.1115/1.4051343.

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Paper VI (study 6)

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Distribution of work: Bayani initiated the idea, designed and conducted the experiment, analysed the results and authored the paper. Wickman and Söderberg contributed as reviewers.

ADDITIONAL WORKS

Paper A-I (study A1)

M. Bayani, K. Lindkvist, M. Tang, L. Lindkvist, C. Wickman, and R. Söderberg, "(accepted for publication) Geometric robustness and dynamic response management by structural topometry optimisation to reduce the risk for squeak and rattle," *Design Science Journal*.

Distribution of work: Bayani initiated and developed the idea, proposed and formulated the theories and methods, analysed the data, authored the paper and actively supervised the model preparation, simulations and post-processing of the results. K. Lindkvist and Tang prepared the models and scripts, ran the simulations and post-processed the results. L. Lindkvist gave technical support for virtual simulation and reviewed the paper. Wickman and Söderberg contributed as reviewers.

Paper A-II (study A2)

M. Bayani, C. Wickman, and R. Söderberg, "Effect of temperature variation on the perceived annoyance of rattle sounds in the automotive industry," in *23rd International Congress on Acoustics*, Aachen, Germany, 2019, pp. 4397–4404. doi: 10.18154/RWTH-CONV-240015.

Distribution of work: Bayani initiated the idea, analysed the results, authored the paper and actively supervised students to collect the data. Wickman and Söderberg contributed as reviewers

Paper A-III (study A3)

M. Bayani, A. P. Székely, N. Al Hanna, H. Viktorsson, C. Wickman, and R. Söderberg, "Nonlinear modelling and simulation of impact events and validation with physical data," in *Conference Proceedings of ISMA2018, International Conference on Noise and Vibration Engineering*, Leuven, Belgium, Sep. 2018, pp. 4299–4313.

Distribution of work: Bayani initiated and developed the idea and collected the experimental data. Bayani, Székely and Al Hanna collected the simulation data, analysed the data and authored the paper. Viktorsson contributed with technical support for virtual simulations. Wickman and Söderberg contributed as reviewers.

Master's Thesis I (study A4)

A. D. Krishnaswamy and C. Sathappan, "Multidisciplinary Optimisation of Geometric Variation and Dynamic Behaviour for Squeak & Rattle," Master's thesis, Chalmers University of Technology, Gothenburg, 2020. [Online]. Available: https://odr.chalmers.se/handle/20.500.12380/301763.

Bayani initiated and developed the idea, proposed and formulated the theories and methods, analysed the data, actively supervised the model preparation, simulations and post-processing of the results throughout the master's thesis work and reviewed the report. Krishnaswamy and Sathappan developed the models, ran the simulations, post-processed the results and authored the report.

Master's Thesis II (study A5)

V. Kulkarni and S. M. Nairy, "Squeak and Rattle Sound Database and Acoustic Characterisation," Master's thesis, Chalmers University of Technology, Gothenburg, 2019. [Online]. Available: https://odr.chalmers.se/handle/20.500.12380/256688.

Distribution of work: Bayani initiated and developed the idea, devised the data collection procedure, developed the post-processing methods, actively supervised the students throughout the master's thesis work and reviewed the report. Bayani, Kulkarni and Nairy collected, post-processed and analysed the data. Kulkarni and Nairy authored the report.

TABLE OF CONTENTS

Abstract iii
Acknowledgements v
Appended Publications vii
Additional Works ix
Table of Contents xi
List of Acronyms xiii
List of Figures xv
1. Introduction 1
  1.1. Squeak and Rattle 2
    1.1.1. What Are Squeak and Rattle Sounds 2
    1.1.2. Significance of the Subject 2
    1.1.1. Current Status 2
  1.2. Scientific Mission 4
    1.2.1. Research Goal 4
    1.2.2. Research Questions 4
    1.2.3. Scientific and Industrial Relevance 5
    1.2.4. Delimitations 5
  1.3. Thesis Structure 6
2. Frame of Reference 7
  2.1. Squeak and Rattle Sounds 8
    2.1.1. Definition and Sound Signature 8
    2.1.2. Common Squeak and Rattle Problems and Solutions 11
  2.2. Squeak and Rattle Prediction and Verification 12
    2.2.1. The Product Development Process 12
    2.2.2. Squeak and Rattle Detection, Rating and Classification 12
    2.2.3. Experimental Squeak and Rattle Analysis 14
    2.2.4. Virtual Methods for Squeak and Rattle Analysis 18
  2.3. Optimisation 22
    2.3.1. Multi-Objective Genetic Algorithm 23
3. Research Approach 25
  3.1. Research Frameworks 26
    3.1.1. Design Research Methodology 26
  3.2. Research Design 27
    3.2.1. The Employed Research Methodology 27
    3.2.2. The Big Picture of The Research Framework 27
    3.2.3. Research Success Criteria 28
    3.2.4. Data Collection Methods Employed 29
4. Results 31

4.1. Parameters Contributing to Squeak and Rattle Analysis ... 32
4.2. The Outline of the Conducted Studies ... 34
4.3. Study 1 (Paper I): Empirical Characterisation of Friction Parameters for Non-Linear Stick-Slip Simulation to Predict The Severity of Squeak Sounds [16] ... 35
4.4. Study 2 (Paper Ii): Finite Element Model Reduction Applied to Nonlinear Impact Simulation for Squeak and Rattle Prediction [131] ... 39
4.5. Study 3 (Paper Iii): A Strategy for Developing an Inclusive Load Case for Verification of Squeak and Rattle Noises in the Car Cabin [127] ... 40
4.6. Study 4 (Paper Iv): Resonance Risk and Mode Shape Management in the Frequency Domain to Prevent Squeak and Rattle [147] ... 43
4.7. Study 5 (Paper V): Squeak and Rattle Prevention by Geometric Variation Management Using a Two-Stage Evolutionary Optimisation Approach [149] ... 46
4.8. Study 6 (Paper Vi): Analysis of Sound Characteristics to Design an Annoyance Metric for Rattle Sounds in the Automotive Industry [17] ... 49
4.9. The Proposed Squeak and Rattle Prediction Framework ... 51

5. Discussion ... 57
5.1. Answering the Research Questions ... 58
5.2. Scientific and Industrial Contribution ... 61
5.3. Reflection on the Research Outcomes Based on the Success Criteria ... 63
5.4. Quality of the Research Outcomes ... 65
5.4.1. Verification of the Work Carried Out ... 65
5.4.2. Validation of the Findings in This Work ... 65
5.5. Positioning the Research Outcomes within the Field ... 67

6. Conclusions ... 69
6.1. Conclusions ... 70
6.2. The Outlook ... 71

References ... 73

LIST OF ACRONYMS

CAD – Computer-Aided Design
CAE – Computer-Aided Engineering
CAT – Computer-Aided Tolerancing
CFD – Computational Fluid Dynamics
CMS – Component Mode Synthesis
CMQ – Current Model Quality
CPA – Contact Point Analysis
DOF(s) – Degree(s) of Freedom
DPA – Digital Pre-assembly Analysis
DRM – Design Research Methodology
FEM – Finite Element Method
GA – Genetic Algorithm
ISF – Incremental Space filler
MAC – Modal Assurance Criteria
MAE – Mean Absolute Error
MIC – Method of Influence Coefficients
MOA – Multi-objective Optimisation Approach
MOGA – Multi-Objective Genetic Algorithm
MOR – Model Order Reduction
NMD – Normalised Max Difference
NRMSE – Normalised Root-Mean-Squared-Error
NSTD – Normalised Standard Deviation
NVH – Noise, Vibration and Harshness
PA – Psychoacoustic Annoyance metric
pph – Parts per hundred
RT – Room Temperature
RQ – Research Question
S&R – Squeak and Rattle

LIST OF FIGURES

Figure 1: (a) The share of noise-related complaints in all customer complaints (12.1-19.1%), and (b) the composition of S&R noise complaints among all noise-related complaints in passenger cars, based on the retrieved data from J.D. Power report in 2017 [5]. 3

Figure 2: Schematic illustration of the stick-slip event. 9

Figure 3: Sound pressure level spectrum for a polymeric pair rattle (a) and a polymer-steel pair rattle (b). The nonstationary loudness (DIN 45631/A1) and sharpness (DIN 45692) curves for the same rattle sounds are given in (c) and (d). 10

Figure 4: Sound pressure level spectrum for a polymeric pair squeak in the side door (a) and a polymeric pair squeak in the instrument panel (b). The nonstationary loudness (DIN 45631/A1) and sharpness (DIN 45692) for the same squeak sounds are given in (c) and (d). 10

Figure 5: Scatter plot of the psychoacoustic and statistical metrics calculated for the cloud of S&R sound database. 11

Figure 6: Belgian pave road surface [71]. 15

Figure 7: The climatically controlled four-poster rig at Volvo Car Corporation. 15

Figure 8: (a) An instrument panel mounted on a subsystem test rig in a climatically controlled semi-anechoic chamber at Volvo Car Corporation, and (b) a quiet component shaker... 15

Figure 9: Stick-slip test machine, SSP-04 from Ziegler-Instruments [75]. 16

Figure 10: Two triaxial piezoelectric accelerometers located on the cockpit left cover to measure the relative motion between the two parts. 17

Figure 11: Listening room for conducting subjective listening surveys. 18

Figure 12: The Design Research Methodology framework, redrawn from [123]. 27

Figure 13: Research results presented in different publications as they contribute to answering the research questions stated in section 1.2.2 and different stages of the DRM framework [123]. The size (small or big) of the stars (*) and RQ denotes the contribution level (low or high) of a study to the respective DRM stage or RQ. 28

Figure 14: Squeak and rattle cause-and-effect diagram. 32

Figure 15: Positioning the studies conducted within this PhD project respecting the study fields and the research questions. The numbers in brackets give the reference number.. 35

Figure 16: (a) The Coulomb static and kinetic friction coefficients and the rate weakening (Stribeck) and viscous regions. (b) Friction formulation using exponential decay coefficient for the rate weakening region [16]. 36

Figure 17: (a) The flexure-based stick-slip test bench (b) Finite element model of the stick-slip test bench with (1) the material sample and (2) the flat board of the counter material [16]. 37

Figure 18: Squeak risk priority number, RPN, for different material pairs versus (a) normal load changes and (b) driving velocity changes in stick-slip experiments. 38

Figure 19: Finite element model of the side door. (a) Different substructure interface

definitions (D8, D40 and D90), (b) the reduced linear and non-reduced nonlinear substructures of the side door according to [131]. 40

Figure 20: Synthesised S&R design parameters for detecting and merging significant events from the reference excitation signals [127]. 42

Figure 21: (a) The proving ground for collecting the reference S&R road disturbances, (b) the complete vehicle at the four-poster rig, (c) the instrument panel in the subsystem shaker rig, (d) the FE model of the instrument panel [127]... 42

Figure 22: Relative displacement and S&R severity factors at the bottom-right corner of the side door assembly estimated from the system response excited by the synthesised Pave disturbance [147].. 45

Figure 23: Schematic depiction of the assembly of two parts.. 47

Figure 24: Jurors' self-consistency vs concordance relative to other jurors, with 1.0 denoting 100% consistency/concordance [17]. 50

Figure 25: Observed and predicted annoyance levels [17]. 51

Figure 26: Squeak and rattle prediction framework. The numbers in parentheses give the corresponding study number conducted in this PhD research that can be retrieved from Figure 15 and sections 4.3 to 4.8. 55

I

INTRODUCTION

This chapter provides a brief introduction to the research documented in this thesis by reviewing the background of the work, project goals and research questions.

1.1. SQUEAK AND RATTLE

1.1.1. What Are Squeak and Rattle Sounds

Squeak and rattle (S&R) refer to irregular and annoying sounds generated in a product as a result of a relative motion and contact between two adjacent parts. Compared to stationary sounds in a passenger car, like the noise from the engine, wind and tyres, S&R sounds are unexpected in a product. Demonstration of S&R in a product is understood as a failure indicator by the users. S&R sounds can develop when two parts unstably slide against each other (squeak) or due to the frequent normal impacts between two components (rattle). Common examples of rattle noises in the car cabin include rattling of the glove compartment lid, centre display or air vents in the instrument panel and rattling of inner panel trim or armrest in the side door. Common examples of squeak are the squeaking noise from weather-strip or chrome panel in the side door, centre display, and air vents in the instrument panel and the sliding or opening mechanisms in the tunnel console. The cause of S&R is mainly the structural vibrations induced by the road surface, powertrain, or the operational loads at low frequencies up to 200 Hz. However, the sounds generated have mid- to high-frequency content up to 2 kHz and 5 kHz for rattle and squeak sounds, respectively.

1.1.2. Significance of the Subject

Perceived quality [1] not only shapes the personality of an automotive brand but also plays an important role in making a profit from a product. Among different quality aspects, interior sounds in passenger cars play an important role in the user perception of the functional quality and health of the car and its systems [2]. A considerable contributor to expenses in aftermarket services among automakers is the cost related to the complaints about the interior sound quality, both for premium brands and volume auto-makers [2]–[6]. A survey, carried out by J.D. Power [5], showed that noise-related complaints count for 12.1% to 19.1% of the total customer complaints in passenger cars in different markets. The report also indicates that about 40% of the noise-related complaints in a car (interior systems, car closures and seats) can be related to S&R sound quality issues, as presented in Figure 1. Indeed, the existence of S&R in a product is perceived as a quality defect by the user and often leads to a workshop referral. Therefore, eliminating the quality issues related to S&R not only promotes a brand but is also a cost-saving measure. To stay competitive, there is a strong growing tendency towards detection and elimination of S&R sounds in auto-makers. In passenger cars, advancements in electrification, the introduction of autonomous driving and the consequent new use cases, such as sleeping, living and working in a car [7], and the quieter in-cabin environment, due to improvements in emitted operational sounds [8], [9], further stress the continuous need for elimination and refinement of nonstationary noises in the car cabin, including S&R.

1.1.1. Current Status

Car manufacturers endeavour to deal with quality issues earlier in the product development process, to avoid expensive post-design-freeze changes. Enormous effort is devoted to shifting engineering activities to pre-design-freeze phases in the development process when affordable concept related solutions can be found and employed. As far as S&R is concerned, traditional problem detection and solving rely on the subjective judgement of hands-on engineers with a find-and-fix approach [6], [10]. To facilitate the treatment of S&R issues in the pre-design-freeze phases without the need for physical complete vehicle prototypes, tools and methods are needed. However, the complexity of the prediction process of S&R sounds and their generation mechanisms has been an obstruction to the practical development of virtual methods for S&R detection. This complexity originates from the sporadic and nonstationary nature of S&R sounds that complicates the virtual simulation of the events. While analysis methods for noise, vibration and harshness (NVH) in automotive engineering are considerably well-developed for the stationary phenomena [8], [9], [11], S&R simulation, in practice, is mainly limited to the linear finite element method (FEM) [2] using simplified evaluation metrics. NVH analysis methods have been mainly developed for stationary phenomena such as powertrain and tyre noise and vibration, the operational sound quality of the subsystems in the car or the wind noise, while S&R analysis requires techniques that are adapted for nonstationary events.

Computer-aided engineering (CAE) should be considered as the ultimate means for the prediction and prevention of S&R problems in the design phase of product development. In addition, the use of subsystem test rigs can be considered as a complementary or intermediate solution. To facilitate this, assessment and verification tools and methods need to be adjusted and further developed accordingly. In this respect, substituting quantitative objective requirements for qualitative subjective methods is inevitable. In other words, besides efficient robust tools, tried and trusted metrics are required to enable a reliable and robust prediction of the S&R risk in a car in good time. Further work is needed to develop new metrics based on calculated kinematics and kinetics of mechanical impact and sliding events and to understand the relation between the sound quality metrics and contact mechanics parameters. The modelling details might need to be adjusted according to the new objective parameters. Further, to enable the involvement of S&R requirements in the design optimisation loops, objective metrics and robust virtual analysis methods are needed. All these are required to be encompassed in a framework that holds the different pieces of the prediction elements together. Such a framework, which covers a wide range of activities in different engaged domains in the prediction process of S&R sounds, is currently missing in the industry.

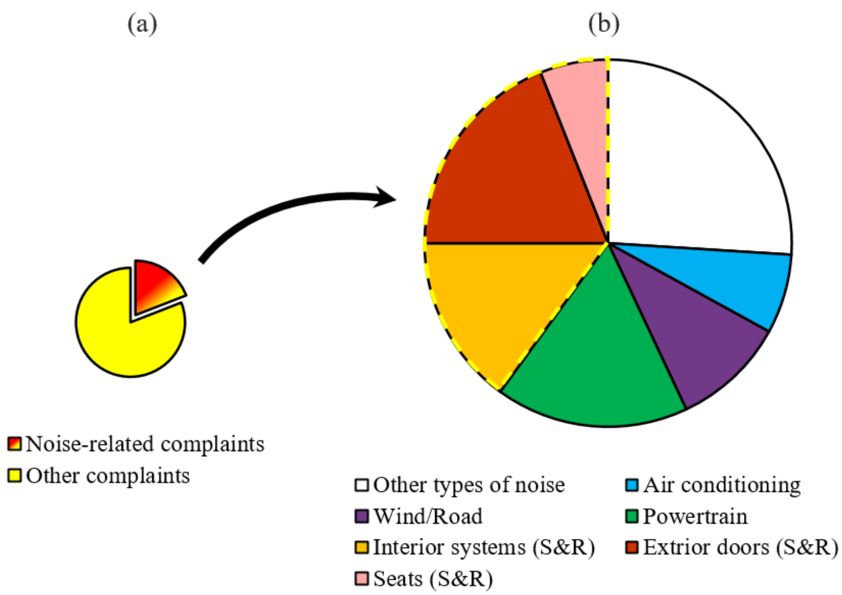


Figure 1: (a) The share of noise-related complaints in all customer complaints (12.1-19.1%), and (b) the composition of S&R noise complaints among all noise-related complaints in passenger cars, based on the retrieved data from J.D. Power report in 2017 [5].

1.2. SCIENTIFIC MISSION

1.2.1. Research Goal

As stated in section 1.1.1, the industrial need for a complete pre-design-freeze verification process of the S&R status in the automotive industry should be addressed by using robust tools and methods. Furthermore, the complexity of the S&R problems has resulted in the unsatisfactory implementation of the available NVH tools and methods directly to rectify the S&R problems. Thus, the main goal of this research can be stated as follows:

- To identify, further improve and support the applicability of an analysis framework for the pre-design-freeze prediction and verification of squeak and rattle noises in the automotive industry.

By developing such a framework, it is expected that this research has achieved the three main objectives of improving the knowledge about some of the needed pieces of the puzzle for developing such a framework to avoid the occurrence of S&R, enhancing the prediction capabilities in the pre-design-freeze phase by investigating the contributing elements to this framework and proposing solutions and methods to address them and further demonstrating the applicability of the proposed solutions in the automotive industry.

1.2.2. Research Questions

Based on the research goals and the identified gaps through literature and field studies, the following research questions were formulated and addressed in this work.

RQ1: *To objectively evaluate squeak and rattle sounds, what elements are needed to establish a robust prediction framework?*

This research question is framed to identify different activities needed in different disciplines to predict the S&R sounds in the pre-design-freeze phase of the product development process in the automotive industry. By referring to the literature, accessible and available industrial resources and field studies, the main elements of a prediction process, the domains they belong to and the main contributing parameters must be identified.

RQ2: *How to improve the currently available tools and methods for including the elements involved in the squeak and rattle prediction framework?*

By referring to the findings from the answers to the first question and conducting descriptive studies, the current level of maturity of the prediction methods can be determined. Further, the potentials for improvement of these methods and the knowledge gaps hindering the development of the methods can be identified. Through descriptive and prescriptive studies, these knowledge gaps are explored and solutions are proposed for further developing the S&R prediction framework.

RQ3: *How can the proposed framework be used in the product development process prior to the design-freeze phase?*

In order to maximise the applicability and industrial relevance of the identified framework and the proposed enhanced prediction methods, the proposed solutions can be implemented in industrial cases. Through descriptive studies, the application of the proposed methods in the industrial problems can be demonstrated and the usefulness and applicability of the outcomes of this research can be judged.

1.2.3. Scientific and Industrial Relevance

This research project deals with academic-scientific challenges and industrial-technological considerations. The problem at hand was initiated from an industrial need: the necessity of dealing with S&R problems before the design-freeze phase in the automotive industry. However, the research presented here also addresses the fundamental theoretical formulations of the problem with the goal of improving knowledge about the characteristics of the phenomenon under study.

As far as the scientific relevance is concerned, the research aims to expand the theories for quantifying S&R events, that are expandable to other nonstationary types of sound. Also, the research covers the exploration of virtual analysis methods of S&R, identifying the potential points for improvement to accord the evaluation methods and to study some of the contributing parameters behind the S&R generation.

Considering the industrial relevance, this project addresses the need for having a S&R analysis framework by developing such a framework and further studying and improving the tools and methods needed within the devised framework. This includes improving the assessment criteria by replacing qualitative methods with quantitative methods or improving existing objective metrics both for sound analysis and structural dynamics behaviour. In addition, the modelling and simulation approach to support the S&R prediction requires to be improved. Accordingly, simulation methods, including the pre- and post-processing, are enhanced. Although the study cases are taken from passenger cars, the principal theories developed will be applicable in other industrial disciplines where impulsive structural vibration induced sounds have importance, such as aeronautical and ground vehicle industries, home appliances and construction industries.

1.2.4. Delimitations

There are different contributing factors to studying the S&R sounds, their cause, impact, and rectification. S&R sounds in a product are perceived by humans and this perception can be studied under psychoacoustics. The sounds, their signature and significance can be studied under acoustics. Ambient conditions, ageing and degradation, manufacturing quality, user experience and expectations, brand signature, driving conditions and background noise, as well as the utility purpose, are among the known factors influencing the evaluation of S&R sounds. The study of system behaviour as the structural vibration can be addressed by structural dynamics. The virtual simulation of the dynamic response of the system is covered by numerical methods in mechanics for noise and vibration. Signal analysis, from pre-processing and system excitation to post-processing and response quantification is done under the signal processing domain. Therefore, to completely address the problem, extensive research work is needed to study the cause-and-effect of the contributing factors in all involved disciplines and domains. However, the work presented here focuses more on developing a framework for S&R analysis to be employed in the pre-design-freeze stages and by a higher weighting for virtual simulations. Although some studies included in this work address some of the contributing factors, the main objective of the studies was to better understand the pieces of the puzzle needed to form the prediction framework. Indeed, the selection of the contributing factors to be included in the in-depth studies in this PhD project was made based on the following factors. In the first place, priority was given to the factors with the most fundamental contribution to the S&R prediction and simulation process. These factors were supposed to be essentially required to establish a prediction framework for S&R. The contribution levels were set with reference to the knowledge attained during the literature and field studies using the industrial and academic resources. Next, the contributing factors that were commonly cited in the literature as major contributors to the generation of S&R were given higher weight. Lastly, the availability and simplicity of the relevant methods, tools and knowledge to tackle a contributing factor was considered as a determining factor for choosing the study subjects.

In the series of works conducted in the present PhD research, the study cases were taken from the automotive industry and with a focus on the interior subsystems that are more prone to S&R problems. These subsystems included the instrument panel, doors and seats that are reported to be the main origins of S&R in a car [2], [6], [12]. The reason for this was to deal with the cases with higher significance due to proximity to the car users. Nevertheless, the principles behind the problem and the theories governing these phenomena are the same in other similar industrial cases. Therefore, it is assumed that the findings from this research hold true for other equivalent settings or in other similar applications.

Where controlled sound and vibration signals were needed, laboratory apparatuses were used to allow control over the test conditions. Since repeating tests to generate S&R sounds in the car cabin, especially due to road surface excitation, does not lead to identical results, using a laboratory environment helps to achieve repeatability in the research. Also, generating S&R sounds in the car cabin under desired controlled conditions is a hard task to achieve, if not impossible. In the selection and design of the test devices, special care was given to maintaining the acceptance and validity of the research by referring to the accepted norms and methods within the field, such as the flexure-based stick-slip test bench [13]–[16] or the rattle producing machine [17]–[20]. For the subjective tests, the expert panels were mainly chosen from the analysis engineers working with the S&R sounds as their profession in the automotive industry. Practicality and ease of access to these expert panels drove this choice. In the virtual analysis, finite element (FE) models of the structures were used, and the coupling to the computational fluid dynamic models of the volume for acoustic simulation was skipped. The main reason for this was to try to quantify S&R in affordable ways, considering available computational resources in the industry. Nevertheless, this coupling can be the topic for future studies that can be built upon the outcomes of this work.

1.3. THESIS STRUCTURE

This thesis report is divided into six chapters. In the first chapter, a brief description of the phenomenon under study and its industrial and scientific significance is given. The scientific mission of this research is stated as the main goal, and the research questions, the scientific and industrial relevance and the boundaries of the conducted research are described. In the second chapter, a definition of the phenomenon as perceived by the author, a brief review of the available prediction and evaluation tools and methods and an introduction to the central concepts involved in this research are given. Chapter three deals with the methodology employed in this research and the data collection methods employed. In chapter four, the results of the research, the main outcomes and their industrial and scientific relevance are reviewed. The answers to the research questions are given in chapter five, followed by a brief review of the main industrial and scientific contributions of the outcomes of this work, and a discussion on the validity and acceptability of the studies performed. In the sixth chapter, the entire work is summarised and an outlook for the future works is given.

2

FRAME OF REFERENCE

In this chapter central concepts and theoretical backgrounds governing the main disciplines engaged in the research presented in this thesis are addressed.

2.1. SQUEAK AND RATTLE SOUNDS

2.1.1. Definition and Sound Signature

In a car, the emitted sounds can be categorised into two groups of stationary and nonstationary sounds. The stationary sounds, as the name suggests, encompass sounds with constant or slowly changing or continuously changing characteristics. The common stationary sounds in a passenger car are the powertrain noise, the tyre noise, the wind noise, and the operational sound of the mechanisms inside the car cabin. In contrast, nonstationary sounds have sporadic and irregular characteristics. They are impulsive and usually last for a short duration but can occur frequently. S&R sounds are the most common nonstationary sounds in a passenger car that are unexpected by the users, unlike the stationary sounds, such as the powertrain sound that is usually sound designed in passenger cars. As mentioned in 1.1.2, the presence of S&R in a car is perceived by the users as a quality defect and failure indicator that often leads to a workshop referral. Thus, premium automotive manufacturers and mass producers invest heavily in avoiding the generation of S&R sounds in their products.

Squeak is a friction-induced noise, like squeal and creak noises. These are the sounds that are generated when two parts with relative planar movement slide against each other resulting in instabilities at specific relative speeds and normal loads. Squeak has varying frequency content that usually occurs at relatively lower frequency bands compared to squeal and has less impulsive characteristics compared to creak noise [21]. One of the main phenomena attributed to the generation mechanism behind the squeak sound is the stick-slip phenomenon that origins from the tribological instabilities [22]. Stick-slip instabilities are related to the variations in the friction force, which is related to the alterations in friction coefficient or the normal force [13], [14], [23]. The schematic description of a stick-slip event as the friction force acting in the contact surface of two sliding parts is illustrated in Figure 2. At the start of the relative motion, the two parts stick together as the reaction force increases. During this period, the motion energy is stored in the parts in the form of the elastic strain energy by the local elastic deformations at the interface. When the reaction force reaches the static friction force limit, a drop in the friction force happens to the so-called dynamic friction force. As a result, the stored elastic strain energy bursts into kinetic energy and the two surfaces start to slip. This kinetic energy is quickly exhausted due to the confronting friction force and the viscous damping and shortly the two parts stick together again. When squeak producing stick-slip events happen, this cycle continues in an unstable loop, resulting in an impulsive vibration in the surface of the part. This unstable impulsive vibration is the cause of squeak sounds and depends on the relative speed between the two parts, the acting normal force, surface profiles, material characteristics and the ambient conditions. A slight change in any of the above-mentioned parameters can change the frequency and properties of the stick-slip event, thus making it a very unstable phenomenon. Although the difference between the kinetic and static friction coefficients was considered as the cause of stick-slip in early studies [24], later the negative slope of the friction coefficient and relative velocity curve has been described as the cause of the stick-slip events [6], [14], [15], [22], [23], [25]–[27]. The negative slope of the friction coefficient vs relative velocity is called the rate weakening or the Stribeck effect [22], [23]. It was analytically proven [23] that the rate weakening effect is a necessary but not enough condition for the occurrence of friction-induced instabilities leading to stick-slip events. Indeed, the rate weakening effect results in a decrease in the dry friction force when the relative velocity increases that contrasts the decelerating effect of the viscous damping.

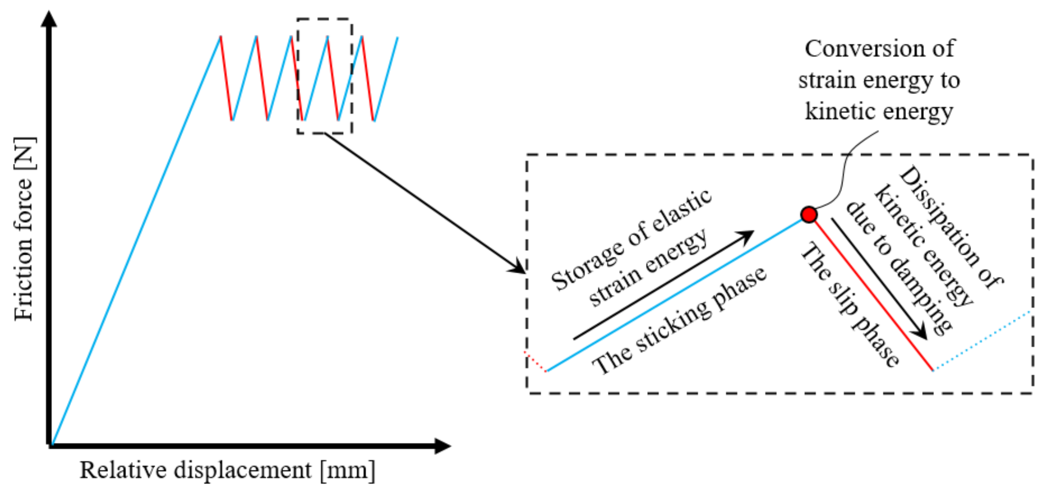


Figure 2: Schematic illustration of the stick-slip event.

Contrary to squeak sounds, rattle is an impact-induced sound that is generated because of the impact between two solid surfaces. Akay [28] reviewed the generation mechanisms of impact sounds. In elastic impact events, four different mechanisms were mentioned to be behind the sound generation [28]. Air ejection is the pressure pulsation that happens in the cavity entrapped between the surfaces in contact. The rigid body radiation is the pressure disturbance created in a medium because of the periodic rigid movements of a part. The other mechanism behind the generation of impact noise is the so-called pseudo-steady-state radiation and is the sound that results from the transient damped harmonic vibrations of the impacting parts. In the impact events involving flexible bodies and plates, radiation due to rapid surface deformation is also a source of impact noise generation. The generated sound, in this case, is in the form of a peak pressure pulse at the start of the impact event, before the pseudo-steady-state sound is generated.

Squeak and rattle sounds are broadband sounds. Squeak sounds are classified as mid- to high-frequency sounds, usually between 500 to 8000 Hz, while rattle sounds usually have lower frequency content in the range of 200 to 5000 Hz [9]. However, the excitation sources causing these phenomena have lower frequency ranges between 20 to 200 Hz, mainly originating from road surface profile, power train and operational vibration induced by the mechanisms in the instrument panel, body closures and seats. As an example, the sound pressure level spectrum of two rattle sounds from inside the car cabin that are generated from a polymeric pair contact and polymer-steel contact is given in Figure 3(a) and Figure 3(b), respectively. The respective nonstationary loudness (DIN 45631/A1) and sharpness (DIN 45692) graphs for these sounds are shown in Figure 3(c) and Figure 3(d). The frequency spectrums of two squeak sounds from the instrument panel and the side door are illustrated in Figure 4(a) and Figure 4(b), respectively. The nonstationary loudness and sharpness curves related to these sounds are given in Figure 4(a) and Figure 4(b).

Figure 5 shows the calculated psychoacoustic metrics and some statistical measures for a wide range of S&R sounds collected from four different cars while driven on the S&R verification tracks in a proving ground [29]. It can be seen that the range of variations for S&R sounds in terms of the psychoacoustic single values and the statistical measures reflecting the temporal properties of the sound is wide. For the definitions of the psychoacoustic and statistical measures see [17].

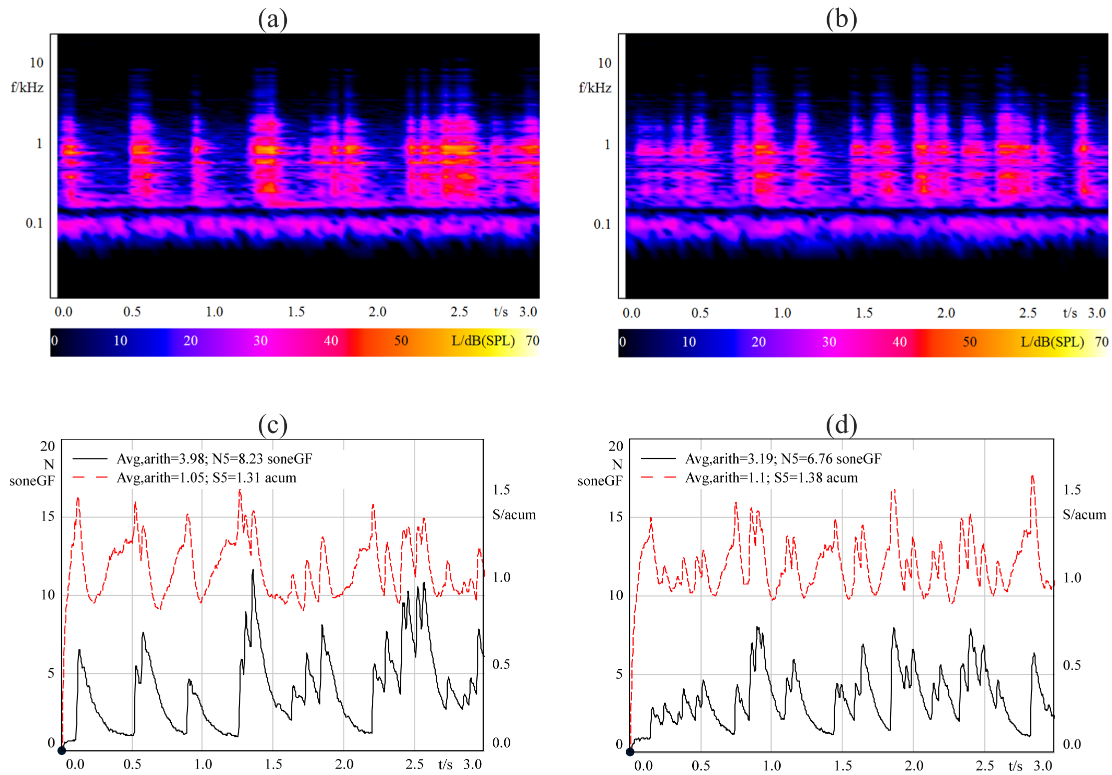


Figure 3: Sound pressure level spectrum for a polymeric pair rattle (a) and a polymer-steel pair rattle (b). The nonstationary loudness (DIN 45631/A1) and sharpness (DIN 45692) curves for the same rattle sounds are given in (c) and (d).

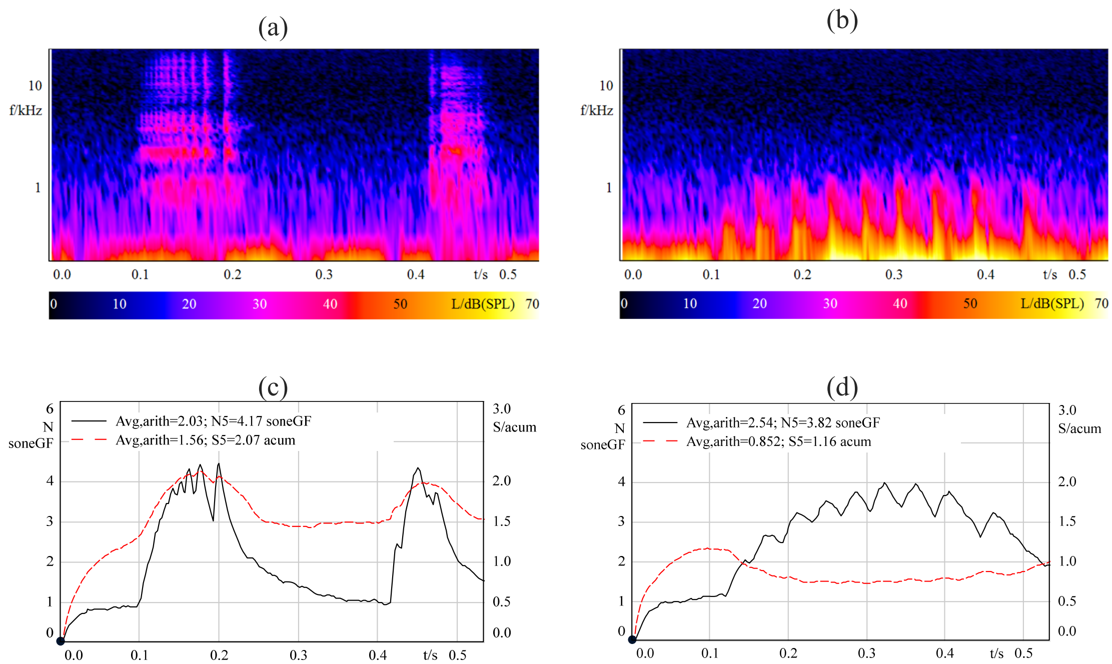


Figure 4: Sound pressure level spectrum for a polymeric pair squeak in the side door (a) and a polymeric pair squeak in the instrument panel (b). The nonstationary loudness (DIN 45631/A1) and sharpness (DIN 45692) for the same squeak sounds are given in (c) and (d).

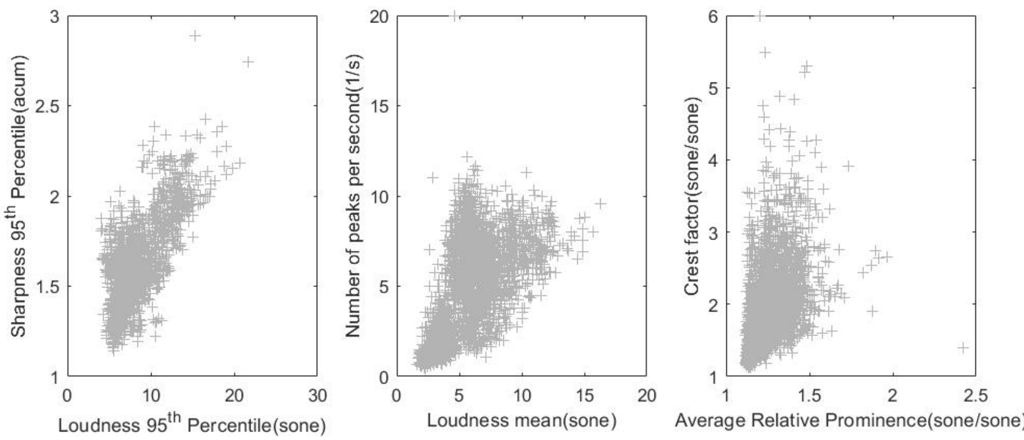


Figure 5: Scatter plot of the psychoacoustic and statistical metrics calculated for the cloud of S&R sound database.

2.1.2. Common Squeak and Rattle Problems and Solutions

In the previous investigations [2], [6], [12], instrument panels, seats and doors were mentioned as the main origins for the customer complaints regarding S&R. It was mentioned that 31% of the customer complaints regarding S&R were instrument-panel related [12]. Another study [2] indicated that instrument panel (42%), door trims (15%) and seats (13%) account for about 70% of the S&R events inside the car cabin.

Common areas for the generation of the rattle noise inside the car cabin include:

- the instrument panel, such as glove compartment lid, steering column attachment, AC louvres and cover panels
- the body closure, such as inner panel trim, armrest, side door pocket, window, speaker attachments, sunroof and wiper mechanism and inner panels in the liftgate
- the seats, including the position adjusting mechanisms in the front seats

The common problematic areas for squeak are:

- the sealings, such as the door sealings
- the body closures, including the window regulator
- the upholstery, such as the seat leather cover
- the instrument panel, including air vents, fasteners, and centre display

To prevent or eliminate S&R sounds in passenger cars, there exist measures that relate to the design concept, including modifying the connection configuration in a subsystem assembly, the choice of connection types and the allowable play, adjusting the clearance targets, the modal separation between connected or adjacent parts, blocking the load transfer passes, stiffening the parts and a considerate material selection. In addition to the concept related solutions, other provisions are also considered that are mainly rooted in the traditional and find-and-fix approaches of treating S&R problems, like adding absorbent materials or lubricants in the contact interfaces and surface treating of parts. Compared to the concept-related measures, the latter counteractions impose high production costs on the car manufacturers and therefore more and more are being outweighed by the concept-related approaches, wherever possible.

2.2. SQUEAK AND RATTLE PREDICTION AND VERIFICATION

2.2.1. The Product Development Process

As Ulrich et al. define, the product development process encompasses all the activities required by an enterprise to conceive, design and commercialise a product [30]. It is the process of bringing a product from an idea to the market. All the relevant activities within the three domains of marketing, design and manufacturing are covered by a product development process. The generic product development process proposed by Ulrich et al. consists of the six main stages of planning; concept development, system-level design, detail design, testing and refinement, and production ramp-up [30]. The commonly employed stage-gate product development system in the industry has the same stages [31]. In the traditional stage-gate approach, requirements are cascaded and set at the different system, subsystem, and component levels. The concept of the stage-gate system is to add a quality control checkpoint or gate between each stage. At each stage, the deliverables are quality controlled against the pre-set requirements at the concept integration and product definition phases. An alternative approach, that has evolved through the software developing businesses, is the agile product development system [32]. The fundamental difference between an agile system and the traditional stage-gate system is the approach to quality control. In the stage-gate paradigm, a separate testing gate always appears after the workstations. In contrast, in the agile approach, development and testing happen at the same stage. The other main difference is that in the stage-gate approach, each stage or step is required to be completed in its entirety before the next stage can start. However, in the agile approach, the cross-functional team in charge of developing a subsystem decides on the release of the sub-product based on its maturity level and upgraded value. In fact, the mindset in the agile system is to support a product, rather than a project in the traditional stage-gate system. Independent from the employed product development system, to evaluate the attributes of a product, such as S&R in the passenger car, measurable requirements are needed to verify a product. Therefore, an attribute evaluation framework is always needed independently of whether the requirements are set at the early stages of the project or through the iterative loops of an agile system. This research aims at identifying such a framework to evaluate the status of S&R sounds in a car before the design is finally judged and frozen and the manufacturing activities enter the tooling stages. This stage is called the design freeze stage in the industry and the development phases before or after this stage are referred to as pre-design-freeze-phases and post-design-freeze-phases in this thesis, respectively. This framework enhances the analysis and prediction capabilities of a product or sub-product from the concept integration phase to the final design judgement, as is called pre-design-freeze phases in this thesis.

2.2.2. Squeak and Rattle Detection, Rating and Classification

In evaluating the status of a product concerning S&R sounds, three main activities can be considered: detection, determination of the problem severity and classification or source identification. This process has been discussed in a few publications, such as [2], [6], [10], [33]. To evaluate and treat S&R problems, the S&R events are needed to be detected in the first place. The next step would be to identify the severity of each event and rank them based on their estimated effect on the product quality. Then, the S&R events are needed to be classified to connect the problems to the known types of causes or sources. Despite the numerous efforts on automating and quantifying different involved activities in S&R evaluation, which can be found in the reference list of this thesis, the prevailed approach for S&R status verification in the automotive industry still relies on subjective physical evaluations [2]. The impulsive and transient behaviour and the complex mechanisms behind the generation of S&R sounds make them hard to predict, measure and detect, rate and classify [2], [10]. It was shown that the low signal to noise ratio of S&R events makes it hard to trace these events in the recorded signals, though they might be distinctly audible by the customers [34]. The use of sound detection and localisation technologies, such as acoustic imaging, for simultaneous detection and localisation of S&R problems in the car cabin was discussed in [10], [35] though they do not have wide applicability in the industry for S&R evaluation.

The efforts on quantifying the detection and rating of S&R sounds date from over two decades ago. Instrumentation, fixation, excitation and detection parameters for a successful evaluation of S&R sounds in an instrument panel was discussed in [33]. The use of quantified metrics to evaluate the sound quality inside the car cabin was briefly reviewed in [36], [37]. In some of the early works [38]–[41] on the automatic detection of S&R sounds, the use of wavelet and statistical measures such as frame kurtosis, crest factor and standard deviation was investigated. The use of psychoacoustic metrics in developing S&R metrics was tried before [35], [40]–[44]. The percentile levels of the loudness have been the most common S&R detection and severity rating metric in the automotive industry [35], [39], [43], [45], [46], especially for component-level testing [10]. Despite the application of psychoacoustic metrics, the percentile levels and frame kurtosis of loudness proved to be partially useful for S&R detection, they showed to be inadequate in severity rating of S&R sounds [10], [35], [40], [41], [43], [44]. Chandrika and Kim [47] suggested using the perceived transient loudness that was calculated as the temporal integration of the summed specific loudness after removing the background noise contributions. By defining a threshold, S&R events could be detected and the magnitude of the proposed metric could determine the severity of the sound. The significance of the temporal magnitude variation of the rattle sounds on their perceived annoyance was reported in [48] and accordingly, the loudness values were adjusted respecting the sound peak decay time quantity using Prony's method.

Lee et al. [18] investigated the use of psychoacoustic metrics to classify the detected S&R sounds, into squeak or rattle categories as an extension of their previous work [47]. The idea of matching an S&R sound to a database of S&R samples to find the sound source using the Fourier and Hilbert transforms was studied by Huertas et al. [49]. Audio fingerprinting, which was originally developed for music identification, was employed by Seo et al. [50] to classify the type of S&R sounds based on a sound database despite its limitations. Later, Pogorilyi et al. [51] investigated the adoption of the landmark-based audio fingerprint technique to automatically match a query S&R sound to the closest S&R reference sound in a database by adjusting the algorithm parameters. They concluded that despite the inefficiency of the method for a large S&R dataset and the inadequacy of the original algorithm in treating the transient behaviour of S&R sounds, by some adaptation, the algorithm could be used for a small S&R database. The idea of using machine learning technology to identify S&R sounds from a recorded sound signal was first studied by Antelis and Huertas [52] by using the method of the neural network. In a similar work, Pogorilyi et al. [53] used neural networks to classify S&R sounds to ultimately identify their source by matching them against a reference database of S&R sounds.

In addition to the application of sound-based objective detection and severity rating of S&R, structural dynamics response parameters were also employed to detect and rate S&R events in the automotive industry. Considering the computational costs and modelling complexities, structural-dynamics-based metrics were the main objective quantities used in the virtual analysis. However, in some of the studies, the approximated sound intensity was calculated from the estimated or calculated impact velocities using the Rayleigh integral method [2], [54], [55]. In some of the works, the S&R severity was calculated from the contact dynamics parameters, such as the maximum acceleration peak [56], the impact velocity [20], [57], the mean squared velocity and the relative tangential velocity during friction events [24], the frequency of the events [2], [58] or thresholds based on the inertial force and preload [59], [60]. In some evaluation methods, a combination of these parameters was used [2], [14], [61]. Friction parameters, such as the difference between static and kinetic friction coefficients [2], [14], the average kinetic friction coefficient [62], the double amplitude of the friction force [26] and the energy dissipation rate [14] were also employed to rate the severity of squeak events from the structural dynamics response in stick-slip events. Linear structural dynamics results were also widely used to objectively detect S&R events and rate their severity. These parameters include the penetration or dwelling time calculated based on the relative motion between the parts, such as [55], [63], [64]. To rate the severity of the detected S&R events, the relative displacement was weighted by the kinetic energy in [65]. Also, the time- and frequency-domain analysis results were used to estimate S&R severity based on the approximated impact velocity, event frequency and impact energy (integration of the relative displacement) [55], [57], [64], [66].

2.2.3. Experimental Squeak and Rattle Analysis

Due to the complexity of S&R sounds, their characteristics, and the mechanisms behind their generation, experimental analysis and verification methods still prevail over the other analysis methods. Here, the common experimental methods and tools used in the product development process for evaluating S&R are briefly mentioned.

2.2.3.1. Excitation Test Rigs

The test subject can be the complete vehicle, either on public roads, or the proving grounds or laboratory test rigs. The common excitation road surfaces used for S&R evaluation have stochastic properties, such as Belgian pave (Figure 6), Vienna blocks, spalled concrete, cobblestone and rough roads, or are frequency-modulated surfaces, such as washboards and rumble strips [67], or transient disturbances, such as potholes, speed bumps, ropes and expansion joints on a smooth road [68]–[70]. The laboratory test rigs simulate the excitations from the road surface by imposing equivalent vibrations either to the whole car, as in a four-poster (Figure 7), or to the car body, called direct body excitation [45]. The advantages of using test rigs, compared to the proving grounds or public roads, are the ease of repeatability, control over the climatic condition, controlled background noise, the possibility of eliminating the powertrain, tyre and wind noise, removing the uncertainties introduced by the human drivers and facilitating physical measurements as well as the objective assessments. On the other hand, the introduction of the additional sources to the background noise, limitation in the excitation frequency imposed by the rig, accessibility to the relevant excitation signals and missing the real driving context in subjective evaluations can be regarded as the main disadvantages of using test rigs rather than the proving grounds or public roads.

The experimental tests can also be conducted at the subsystem level as shown in Figure 8(a). Since the subsystem test rigs have smaller sizes compared to the complete vehicle test rigs, it is more economical to have them in climatic controlled or anechoic chambers. Also, the availability of the physical subsystems earlier during the product development and the related part procurement costs justifies the preference of utilising subsystem-level tests over the complete-vehicle-level test. The subsystem test rigs better suit the agile product development system, as the subsystems can be assessed without the need for the physical complete vehicle prototypes. This also helps to investigate a subsystem isolated from the noises emitted from the rest of the car. However, in defining the boundary conditions and using the fixtures, special consideration should be taken to avoid unrealistic system modelling. The other limitations imposed by the subsystem test rigs are the limitation in the excitation degrees of freedom, limitation in the displacement range vs excitation frequency, the missed in-cabin context and the vicinity of the test subjects to the emitted sounds from the rig shakers. It is also possible to evaluate components of a subsystem with smaller component shaker rigs like the one shown in Figure 8(b). A comprehensive study comparing the results of three different test methods, complete vehicle testing at proving ground and four-poster and subsystem-level test rigs, was carried out in [29]. By referring to the results of the study, the accuracy and adequacy of the laboratory tests compared to the road testing in various driving and ambient conditions were discussed.

Figure 6: Belgian pave road surface [71].

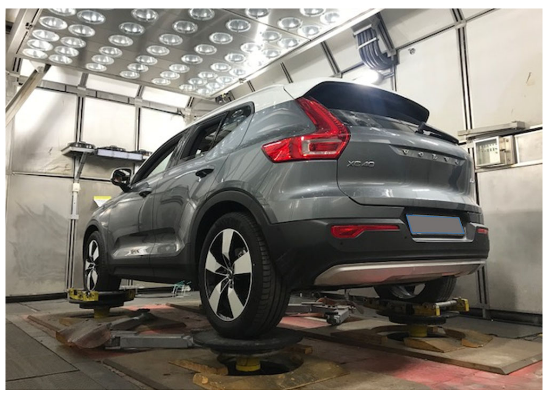


Figure 7: The climatically controlled four-poster rig at Volvo Car Corporation.

(a) (b)

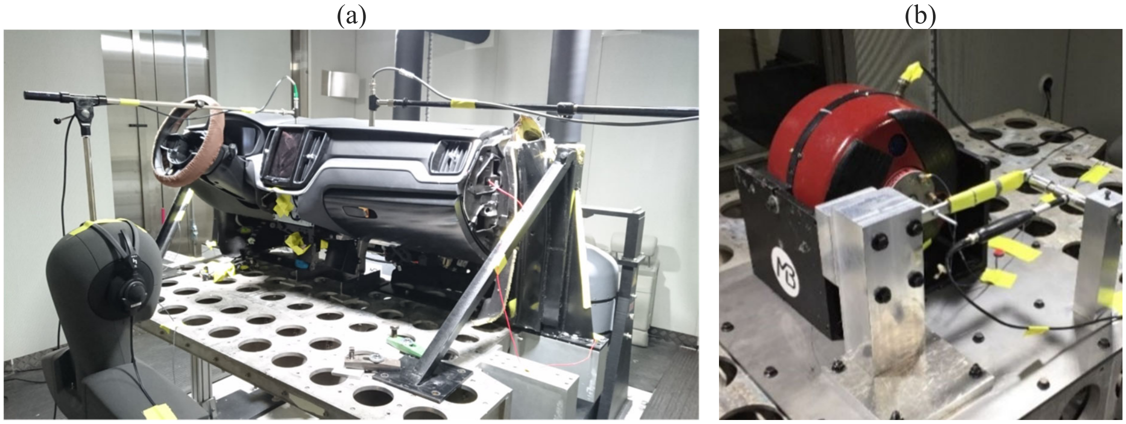


Figure 8: (a) An instrument panel mounted on a subsystem test rig in a climatically controlled semi-anechoic chamber at Volvo Car Corporation, and (b) a quiet component shaker.

The other important parameter that risks the credibility of using laboratory test rigs is the definition and selection of the excitation signals in the interfaces of the car or its subsystems with the test rig. Using the random vibration control method [72] is the common approach in the automotive industry for S&R analysis [68], [69], [73], mainly due to the ease of signal generation and application. Guidelines for generating stochastic signals with prescribed power spectral density (PSD) for S&R applications were discussed in [68], [69]. Other frequency-dependent excitation methods were also proposed for S&R evaluation, such as a frequency sweep test track [70] and frequency-modulated signals based on the rumble strips [67]. However, the use of the random vibration control approach in analysing S&R events imposes some limitations. Time transient excitations, such as potholes, steps, ropes and expansion joints, cannot be well presented by a random vibration-controlled signal [68] and the stochastic excitations increase the variability of the results [72], [74]. Despite the mentioned drawbacks, the application of synthetic time-history signals has remained limited for S&R evaluation [69], due to the complexity of generating inclusive representations of the reference signals.

Special test benches are used in the industry for testing material samples for S&R applications. The most widely used type is the translational flexure-based stick-slip test bench [13]–[15], such as the one shown in Figure 9 [75]. Using this machine, different material pairs in different ambient conditions and under prescribed preloads and relative speeds can be evaluated for the risk of squeak generation. The characteristics of the stick-slip events including the involved friction parameters calculated from the test results are used to judge the compatibility of material pairs respecting the risk of squeak generation. The car manufacturers build material compatibility matrices by using the results from these tests [15], [26], [27], [62] to minimise the squeak risk by a proper selection of material pairs in the contact interfaces [2], [4], [6].

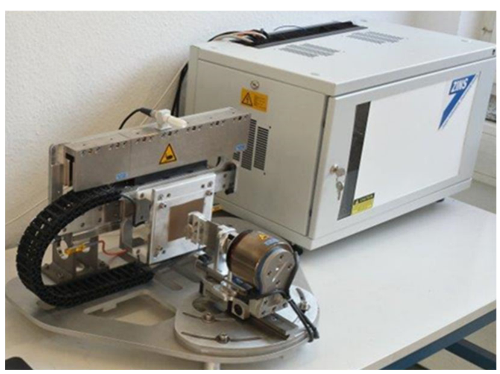


Figure 9: Stick-slip test machine, SSP-04 from Ziegler-Instruments [75].

2.2.3.2. Subjective Evaluation

Subjective evaluation means conducting a qualitative evaluation of the quality of an attribute of a product based on the judgement of the users or experts and analysis engineers. Mostly, subjective tests are done in connection to the testing of a complete vehicle. The main reason is to put the test subjects in the real product context. However, subjective testing is sometimes done at the subsystem or component levels. In the industry, there are internally standardised norms for subjectively grading the quality of a product. Different rating scales from verbal to numeric are used, but the latter, with a scale from one to ten linearly reflecting the quality level, is the commonly used subjective scale for S&R severity rating in the automotive industry.

2.2.3.3. *Objective Evaluation*

By objective evaluation, the response and behaviour of a product or subsystem of a product is measured in the form of quantified metrics. In the verification phase, these measurements are compared to the pre-set requirements for the product. The objective evaluation is often done using the measured response of a system in the experimental tests. However, by evolving the virtual simulation processes, some of these objective metrics are possible to be calculated from the virtual simulation results. Two types of parameters are often collected in the experimental tests in S&R analysis: the sound signal and the vibration response. Vibration response is collected either by accelerometer sensors or laser vibrometers for the direct measurement of the point displacement, although the application of the latter is limited in the industry. To capture the relative movement of two parts at an interface by accelerometers, the type and sensitivity of the sensors (often AC-response accelerometers), the placement of the sensor on the part, noise handling and filtration and the selection of the measurement location influence the measured signal. For the S&R application, it is common to calculate the displacement signals from the measured acceleration signals. This often results in unrealistic drifts in the displacement signal due to the accumulated measurement noise during the double integration process that needs to be treated in proper ways, such as using the method proposed by Mercer [76]. The evaluation criteria, as reviewed in section 2.2.2, are either based on the statistical calculations of the measured acceleration and velocity levels or the calculated relative displacement between the two measured points at the problem interface, as shown in Figure 10.

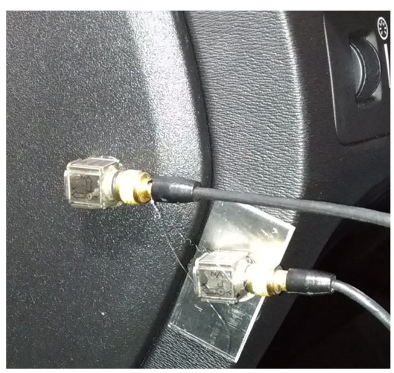


Figure 10: Two triaxial piezoelectric accelerometers located on the cockpit left cover to measure the relative motion between the two parts.

Sound measurement can be done by diffuse-field microphones inside the car cabin or test chamber, or free-field microphones, in the outside environment or anechoic chambers. If the intention of sound measurement is to reproduce the sound in future, binaural sound recording technology is needed. As shown in Figure 8(a), in one of the carried-out studies in this project, the sound emitted from the instrument panel was measured both by two microphones and the BHS II binaural headset mounted on the HMS IV artificial acoustic head, both from Head-Acoustics GmbH. When collecting sounds, the background noise needs to be measured, isolated from the sound source wherever possible. The use of test rigs, compared to public roads or proving grounds, facilitates the background noise measurement process. To detect the S&R events and to assess their quality from the measured signals, objective metrics may be used that are reviewed in section 2.2.2.

2.2.3.4. *Subjective Sound Listening Tests*

To develop objective sound quality metrics, subjective sound listening tests or listening clinics are widely used in the industry. For this purpose, the subjects are exposed to some broadcast sound stimuli and are asked to judge the quality of the played sounds. Different subjective sound listening tests that are commonly used in the automotive industry are reviewed in [77]. The most used methods are the paired comparison method, response (rating) scale, semantic differential, and magnitude estimation. For the description of these methods see [17], [77], [78]. Specific considerations should be taken for sound recording, selection and preparation of sound stimuli, employment of the test method, training of subjects, the communication and media type, the test environment and ambient condition, test duration and difficulty level, sound reproduction and selection of the test subjects [77]. The test can be conducted in a listening room, such as the one shown in Figure 11, or inside the car cabin. The former is widely used in the automotive industry. The subjects can make their judgements using printed questionnaires, as was used in [79], or through a digital interface, as was employed in [17]. It is highly important to check the quality and confidence level of the conducted test by statistical calculations [77]. One way of doing so is to calculate the subjects' self-consistency and concordance as described in [17]. The results from a subjective listening test can be used to design sound quality metrics for the objective evaluation of S&R sounds.

Figure 11: Listening room for conducting subjective listening surveys.

2.2.4. Virtual Methods for Squeak and Rattle Analysis

2.2.4.1. *Contact Point Analysis*

Contact point analysis (CPA), as the process is described by Daams [4], is a procedure to identify S&R risks early in the car development programmes via analysis of digital models. For this purpose, mature 3D CAD models are needed. The analysis is performed during the industrialisation phase of the car programmes. The first analysis occurs at the detail design phase and the final analysis is conducted before the design freeze, during the final design judgement, and therefore sometimes referred to as digital pre-assembly analysis (DPA) in the automotive industry [80]. The evaluation is done by analysis engineers who are experts within the field of S&R and the analysis results are reported to the stakeholders from the design teams. Depending on the maturity level of the CAD, the focus of CPA analysis changes. At the earlier stages, when the CAD has a lower maturity level, the focus is given to the design concepts, including the connection configuration, type of fasteners and material choice. At the later stages, details of the design can be checked using mature CAD models. During the analysis, the requirements at the complete vehicle level and system level, material compatibility matrices, documented knowledge from the previous programmes and products, operational conditions and available geometric variation analysis results need to be referred to. Each component in an assembly is analysed against its neighbouring parts, considering the connection configuration, boundary conditions, clearance in the interfaces and material combinations. The identified risks will be analysed and discussed in a group involving S&R experts, the design teams and CAE engineers. Based on the identified risk level, a decision for further judgement by CAE or physical testing analysis or assignment for design changes to eliminate the risk is made [80]. In the automotive industry, CPA accounts for the first series of S&R analysis activities and is used as a high-level problem detection method.

2.2.4.2. Structural Dynamics Analysis

FEM is the most used virtual analysis method in structural dynamics problems. The main idea behind FEM is to divide a geometrically complex system into smaller parts or to discretise the solution domain. This activity is called the meshing process. In the automotive industry, different commercial mesh generating tools are used, among which Hypermesh© and Ansa© have gained the most popularity. The partial differential equations for the structural dynamics response of the discretised geometrical model are solved by numerical methods and by forming a system of algebraic equations or ordinary differential equations [81]. For simulating S&R events by solving the FEM problems, different commercial tools are used in the automotive industry, such as MSC.NASTRAN© and ABAQUS©, which are among the common FEM solvers for simulating structural dynamics in S&R problems. The results of the FEM analysis can be retrieved in the form of data tables for selected degrees of freedom or sets of elements or used to make two-dimensional graphs or three-dimensional contour plots for the system response. The post-processing graphs can be done in the frequency domain as well. The common post-processing tools used in the automotive industry for S&R simulations are Meta© and Hyperview©, in which some statistical methods for evaluating the results are given in the S&R toolboxes.

The common FEM analysis used for S&R simulation in the industry includes modal analysis, static analysis, time transient analysis and frequency response analysis. The purpose of modal analysis in structural dynamics is to monitor and modulate the mode shapes and the eigenfrequencies of a component or assembly. The effect of modulating resonance properties of the system in reducing the S&R severity was studied previously [57], [59], [65], [82], [83]. Often the results of the modal analysis (the eigenfrequencies) are compared against the modal map of the subsystems in a product like a car. Verification is done with reference to the requirements set on the complete vehicle level or system and component level to reduce the resonance risk. The severity of rattle sounds in a seat structure was found to be dependent on the resonance modes in a virtual study supported by empirical results [82]. With the static analysis, the local and global stiffness of the components in a subsystem is evaluated. As a general design guideline, the risk of S&R generation decreases by increasing the part stiffness [2], as it would result in less flexibility and relative motion between the parts. Transient response analysis is a computational method to calculate the forced dynamic response of a system in the time domain exposed to a time-varying excitation. The excitation can be applied as time-history data of forces or prescribed motions of certain degrees of freedom in the finite element model. The Newton law as a system of equations in a structural dynamics problem can be written in the following form:

$$\mathrm{M}\ddot{q} + \mathrm{C}\dot{q} + \mathrm{K}q = F \tag{1}$$

where M, K and C are the mass, stiffness and damping matrices and F and q are the external load vector and the nodal DOFs vector, respectively. If the mass, stiffness, and damping matrices in the FEM problem can be considered constant during the simulation process, the system is treated as linear and the numerical solution converges faster. In the presence of nonlinearities, such as contact forces, nonlinear material properties or geometrical nonlinearities, the mass, stiffness and damping matrices in equation (1) need to be updated in each iteration of the numerical simulation process. This makes the nonlinear FEM simulations computationally expensive. Grosh et al. [84] presented a nonlinear simulation method to approximate the rattle sounds by approximating the response frequency spectrum based on a simplified hinged beam model. Later, a simulation method was proposed [85] to calculate the impact velocity using an explicit multi-body-dynamic solver and then approximate the impact noise by the boundary element method. The multi-body-dynamic model was constructed based on the eigenmodes of the original system. These methods suffer from the model setup complexities and computational inefficiency for large subsystems. Oppenheimer and Dubowsky [19] proposed a heuristic energy-based criterion to determine the need for considering the dynamic interaction (coupling) between parts in predicting the severity of the impact-induced sounds. The energy-based criterion was based on the results of the rigid base decoupled analysis. In the case of coupled analysis, they suggested representing the impacting parts by impulse response functions. Kreppold [57] described a linear simulation approach that was similar to [55], [64] and used the time- and frequency-domain linear response parameters to calculate S&R severity metrics. Compared to the linear approach, it was shown that the accuracy of S&R evaluation improves using nonlinear implicit contact simulation in terms of impact velocity, event frequency and impact energy. However, it was concluded that to overcome the evaluation uncertainty, the acoustic simulation would be inevitable. In [55], the application of different adopted techniques in predicting S&R events in an instrument panel assembly was presented without giving the details of the calculations. The problem domain was confined using the clearance and threshold evaluations [60] based on the modal and frequency response analysis. Then the sound intensity was estimated using the Rayleigh integral using explicit finite element simulations. In a recent study [86], the harmonic balance method was used to simulate the squeak events in a car side door including frictional nonlinearities and later further improved by considering a variable normal contact force [87]. The system response was approximated by the truncated Fourier series using the harmonics of the fundamental frequency in a harmonically excited system. The increased computational efficiency in the nonlinear simulation of stick-slip events by the harmonic balance method was discussed in [86]–[89].

Even though the robust evaluation of S&R requires an accurate prediction of the kinetics and kinematics of the contact events that generate the S&R sounds [20], [23], [89], [28], [54], [55], [57], [59], [86]–[88], the computational inefficiency of the nonlinear contact simulation in S&R evaluation for mid- to large-scale subsystems has been shown in previous experiments [20], [85], [90], [91]. In practice, virtual simulation of S&R in the automotive industry involves linear finite element analyses, using linear models. In FEM solvers, such as MSC.NASTRAN© and ABAQUS©, linear transient response solution is done either by direct transient response or modal transient response methods. In the direct transient response, the equations of motion are solved as a set of coupled equations by direct numerical integration. For numerically heavy problems, the alternative approach is to use modal transient response analysis. In this method, the system response is approximated as a superposition of the eigenvectors of the system. This results in a set of decoupled equations of motion in the absence of damping in the model, which is computationally more efficient to be solved. However, the uncertainty in the selection of mode shapes involved in the response approximation, the inadequacy for initially conditioned systems and the inefficiency in systems with damping are the considerations that should be taken when employing this approach. For large FEM models, and when a fine resolution in time is needed for the response, the modal transient response method is more applicable. This solution method is one of the most used methods for analysing S&R in the automotive industry. The method introduced in [63] is based on the results from the transient response analysis. System response in critical interfaces for S&R are output as a relative displacement between the predefined node pairs in a FEM model excited in the time domain. The mean value of a fixed percentage of the biggest relative displacements during the excitation time is used as an indication for the risk for S&R. For rattle, this metric is compared against the nominal gap in each interface node pair and a judgement of the risk of generation of rattle is made. The results from the geometric variation analysis can also be considered when the judgement is made to account for the tolerance stack-up effects. For squeak, the same metric is calculated in the contact plane at the node pairs. The metric can be compared to the minimum allowed relative displacement for the respected material pair to avoid squeak sounds, if available. Such data can be extracted from the results of a stick-slip test machine (see section 2.2.3.1), although the available commercial stick-slip machines do not directly output such information today. A similar statistical evaluation can be done based on the force acting between a node pair. The results can be compared to the defined preload in a connection for rattle, or the squeak triggering friction force based on the stick-slip test results. In Meta© and Hyperview©, a post-processing toolbox for this purpose is available.

Frequency response analysis aims at calculating the steady-state structural dynamic response of a system to a cyclic excitation in the frequency domain. Like the transient response analysis, system excitation can be defined by force vectors or prescribed as motion in certain DOFs, but in the frequency domain. Like the transient response analysis, frequency response analysis can either be solved directly or by an approximation of system response in terms of its eigenvectors. The latter is called modal frequency analysis, with the same considerations as the ones mentioned for the modal transient response method. Due to the stochastic nature of the S&R events and their low periodicity, linear time transient simulations might be less time-efficient compared to the frequency response analysis for S&R evaluation [20]. Hsieh et al. [54] proposed to approximate the impact velocity as a function of the system modal parameters (equivalent mass, damping and stiffness and eigenfrequencies) and the input load in a periodically excited system. The method failed to predict the rattle intensity when the excitation frequency was close to the system eigenfrequencies. Frequency response analysis was used in [57], [64] to calculate the rattle risk. But the authors did not give details of the method or how the risk metric was calculated. A similar concept to predict the rattle locations based on the linear frequency response of the system was discussed in [65]. The steady-state relative displacement values in the node pairs were scaled by the kinetic energy to better predict the risk for the generation of rattle events. To overcome the computational cost related to the explicit nonlinear simulations [84], [85], [91], [92], Shorter et al. [20] proposed using a three-step linear simulation process to approximate the impact noises. Firstly, to identify the impact locations by linear frequency domain random vibration analysis using the statistical estimates of the dwell times and impact velocities. Then, the contact forces could be estimated based on the estimated dwell times and impact velocities, the local stiffness, and the point mobility (from the structural dynamics analysis) at the contact point. Lastly, the acoustic radiation was calculated using the statistical energy analysis method. The modal and frequency response analysis results were used in [55] for the initial screening of S&R events in an instrument panel assembly. In another study [66], the eigenvectors of the system were employed to calculate the time-domain displacement response at every eigenfrequency in studying the probabilistic occurrence of rattle events.

2.2.4.3. Geometric Variation Analysis

Geometrical variation is one of the main contributors to the generation of S&R sounds inside a car cabin [2], [4], [93]. The deviation of the geometrical dimensions of a physical part from the nominal design may happen as a result of the tolerance stack-up originating from the introduced tolerances in the connection points in an assembly or the part variation due to manufacturing processes. The introduced geometric variation can cause an interface gap to change from its nominal value. This can result in tighter clearances and increase the risk for the contact between the parts or can change the prescribed preload at the connection points. Geometric variation analysis refers to the virtual simulation of the geometric changes in a part or an assembly as the result of disturbances that can be imposed by part manufacturing or the assembly process. Computer-Aided Tolerancing (CAT) tools [94] are used for the virtual simulation of geometric variation. Different models and methods for geometric variation simulations are reviewed in [95]–[97]. Variation model [98], vector loop-based model [99], deviation domain model [100], Tolerance-Maps® model [101], the technologically and topologically related surfaces (TTRS) [102], [103], skin model shapes [104], [105], matrix model [106], GapSpace model [107], [108] and the Jacobian-torsor model [109], [110] are different tolerance analysis models. The Direct Monte Carlo (DMC) method [111] is the basis of the widely used statistical geometric variation simulation methods by considering the statistical distributions within the defined tolerance ranges in an assembly. Later studies tried to overcome the main shortage of the DMC method, which is its inefficiency in simulating large models and computational cost, such as the Method of Influence Coefficients (MIC) [112], and the other works [113]–[115] to enable efficient robustness and non-rigid variation simulations.

The most used metric, as a calculated value from the geometric variation simulation results, is variations as six times the standard deviation (6σ) and deviation as the difference between the calculated mean value of a dimension and its nominal value. There exist commercial tools for the geometric variation analysis in the automotive industry, such as RD&T© that uses the MIC method, variation model [98] and the point-based method for tolerance analysis [97], [116]. Nevertheless, for S&R prediction, the use of geometric variation simulation is limited to adjusting the nominal static gap values in CPA analysis, as described in section 2.2.4.1, or setting the threshold values for relative displacement results in finite element structural dynamics simulations, as mentioned in section 2.2.4.2.

2.3. OPTIMISATION

Mathematically, an optimisation method aims to find the solutions to a problem resulting in an extremum response from the system. The system response needs to be quantified by using objective functions that reflect the fitness level of a solution. Traditionally, the most challenging task for an optimiser has been to find the absolute optimum value and not to become trapped in the local optima. To address this issue stochastic search approaches are introduced. Contrary to the deterministic optimisation approaches that risk yielding a local optimal solution for high-dimensional, discontinuous and multimodal engineering problems [117], the stochastic search approaches overcome this defect by enhancing the global search. Evolutionary algorithms are branched from stochastic search methods inspired by the evolution processes in nature. Although the evolutionary algorithms are not necessarily guaranteed to find the absolute optimum, they always result in finding good solutions, close enough to the real optimum, if the optimisation problem is framed correctly. Genetic algorithm (GA) is an evolutionary optimisation method that has gained high popularity in industrial applications. GA is based on Darwin's theory of 'survival of the fittest'. At each step of the optimisation, the fittest solutions based on their objective values are selected to build the population for the next generation of solutions. The solutions in each new generation are evaluated and this process continues until reaching the optima. To generate the population in each next generation, genetic algorithm operators are used, among which directional and classical cross-over, selection and mutation are the most employed operators in practice.

2.3.1. Multi-Objective Genetic Algorithm

In an optimisation problem, when the suitability of solutions is defined based on more than one objective function, multi-objective optimisation approaches (MOA) are used. An MOA gives a group of the fittest solutions, the Pareto front solutions, that each result in a set of optimal objective functions. This way, the choice of the best solution can be achieved through a manual trade-off among the conflicting objectives. The MOA methods and algorithms that are widely used in engineering design are reviewed in [118]. The multi-objective genetic optimisation method (MOGA) was first introduced by Fonseca and Fleming [119]. In this method, the fitness of an individual is determined by calculating its domination factor. The domination factor for a solution is the number of individuals performing better than that solution. Thus, the domination factor of the Pareto front solutions is zero. In MOGA, the fitness value is calculated based on the ranking of the individuals with respect to their domination number. To empower the global search, fitness scaling approaches can be used, such as the linear fitness scaling [120].

3

RESEARCH APPROACH

In this chapter, the research design and framework used in the project presented in this thesis is discussed. Further, the methods used in different stages of the scientific studies performed in this thesis are outlined.

3.1. RESEARCH FRAMEWORKS

Design research has two distinctive characteristics: it deals with diversified human activities and tasks; and tries to improve human performance within these complex tasks by introducing practical methods and tools [121]. Therefore, design research is utilised to understand a phenomenon and improve the methods or tools to process its design, creation and evaluation [122]. In the research that is concerned with delivering tools and methods for industrial applications, there are four fundamental study fields: how design is done regarding the phenomenon under study; introducing theories to understand the mechanisms governing the phenomenon; developing tools and methods to model, simulate and predict the phenomenon; and implementing and validating of the developed tools and methods [121], [123]. Design research involves heterogeneous topics and methods. Diversity is in essence of potential merit to create value. However, diversity increases the risk of discrete unconnected research activities that might make it hard to conclude a scientific value for the whole work [124]. This potential risk underlines the need for a methodology to bind all the research activities to achieve results with generic and practical validity. The research presented in this thesis addresses activities in the product development process, in particular, the pre-design-freeze evaluation process of a phenomenon, and is categorised under design research.

3.1.1. Design Research Methodology

Within different design disciplines, diversity of methods and topics raises the risk of lacking mainstream when conducting design research. Design research methodology (DRM) [123] was introduced to overcome this risk by giving a framework to research activities with the aim of increasing the academic credibility and industrial applicability of design-related research studies. DRM framework, as also summarised in Figure 12, consists of four main stages:

Research Clarification (RC), through initial literature and field studies, the main plan for the research is devised. The goals are clarified and set. This stage includes defining the research questions and setting the success criteria in the form of measurable terms.

Descriptive Study I (DS I), in this phase, results of the detailed literature reviews, empirical data and field interviews are employed to give an in-depth description of the phenomenon and the available governing theories. The potential factors for improvement are identified.

Prescriptive Study (PS), the main purpose of this phase is to improve the available technology or knowledge by finding solutions and developing tools to address the identified gaps from the previous phase.

Descriptive Study (DS II), in order to describe the degree of usefulness and applicability of the proposed solutions within the context, the prescribed success criteria are evaluated.

The proposed methodology does not necessarily demand that the prescribed stages are conducted sequentially, and different stages can be done in parallel. Even, in some research studies, some stages of the methodology can be suppressed (or even be excluded) or focused on more [123].

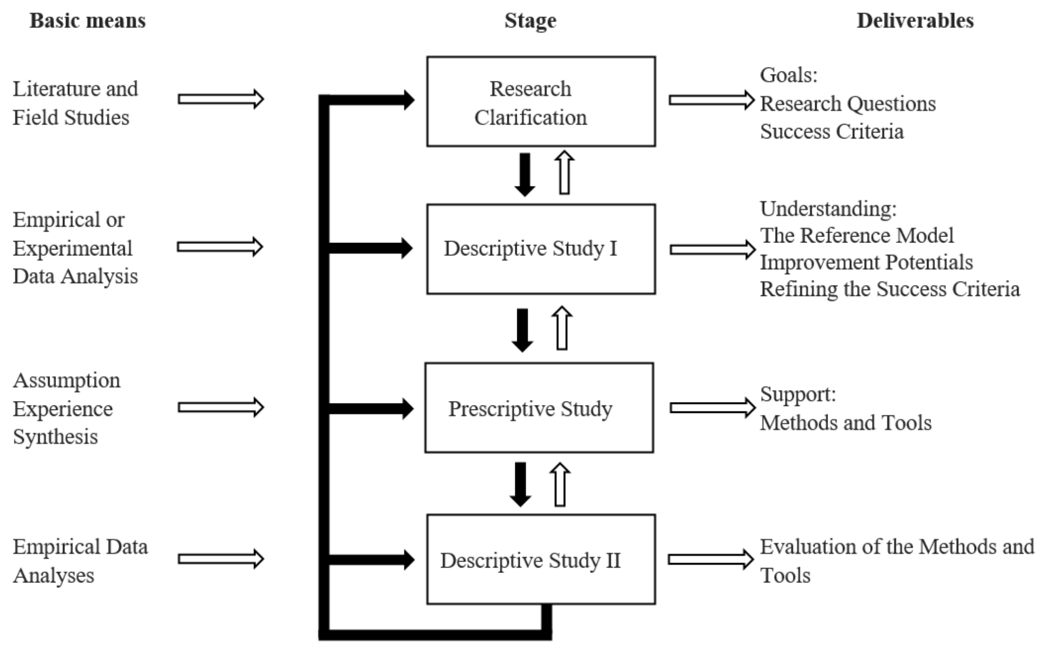


Figure 12: The Design Research Methodology framework, redrawn from [123].

3.2. RESEARCH DESIGN

3.2.1. The Employed Research Methodology

This research work deals with the simulation of an attribute (S&R) of a product (car) in different design and development activities during the product development phases (before the design freeze). Therefore, the research activities fit well in the DRM framework. In modern engineering mechanics, the pragmatic theory prevails over other understandings of truth. In other words, in mechanics, true statements produce useful results if they are put into practice and often the truth of a statement is verified by experiments or observations. The dominant view of knowledge through all performed and planned studies in this research is based on the pragmatic approach with the aim to discover the laws and norms governing the phenomenon under study. To take the pragmatic view in this research work, customisation of the DRM stages, wherever activities required it, was assumed to be valid.

3.2.2. The Big Picture of the Research Framework

The research is divided into different sub-studies. Based on the information gained by referring to the literature, accessible industrial resources and unstructured field interviews and experiments, the status of the problem-solving approaches in the industry and the available knowledge about the governing theories behind the phenomenon under study was reviewed. The data was gathered through different conducted studies, through discussions with experts and by being involved in the development process of the new car programmes in the industry. By integrating the information gathered, the contributing factors to the S&R prediction process were represented in the form of a cause-and-effect diagram and the potential areas for improvement were identified. Through descriptive studies, the industrial and scientific knowledge gaps, hindering the evolvement of the tools and methods, were recognised. By referring to the identified technological and scientific knowledge and potential enhancement capacity, a draft roadmap for a S&R prediction process was devised and a plan of actions was outlined. By performing prescriptive studies, solutions to address the pinpointed gaps were proposed, aiming at enhancing the prediction and evaluation capabilities within the devised prediction framework. This was achieved either by proposing new methods or applying existing methods from other applications to the phenomenon under study. In some of the studies, the proposed methods and solutions were applied to industrial problems to judge their applicability, validity, and generalisability.

Overall, as the research questions are framed, the studies in which the intention was to answer the first research question, belong to the first two stages of the DRM, namely the research clarification and descriptive study I. With these studies, the aim was to answer the first research question by reviewing and understanding the available knowledge about the mechanisms governing the phenomenon, forming the prediction framework and using it as a basis to further explore the problem. To answer the second research question, prescriptive studies were needed, that shape the third stage in the DRM. The second research question concerns improving the evaluation and simulation tools and methods. In this stage solutions to the identified problems are given in the form of tools and methods. For the last research question, where the application of the findings in the industry was the aim, this was addressed by descriptive studies targeting the applicability and validity of the outcomes. These studies by essence belong to the fourth stage of the DRM.

In Figure 13, the structure of the whole research, in the form of the performed studies, the respective research questions addressed by each study and the level of connection of each study to the DRM stages are summarised. A brief review of these studies is given in the results chapter.

	Research Question	RC	DS I	PS	DS II
Study 1 (Paper I)	RQ1, RQ2, RQ3	❋	❋	❋	
Study 2 (Paper II)	RQ2, RQ3	⁎	❋	❋	⁎
Study 3 (Paper III)	RQ1, RQ2, RQ3	⁎	❋	❋	
Study 4 (Paper IV)	RQ1, RQ2, RQ3	⁎	❋	❋	❋
Study 5 (Paper V)	RQ1, RQ2, RQ3	⁎	❋	❋	❋
Study 6 (Paper VI)	RQ1, RQ2	⁎	❋	❋	

Figure 13: Research results presented in different publications as they contribute to answering the research questions stated in section 1.2.2 and different stages of the DRM framework [123]. The size (small or big) of the stars (⁎) and RQ denotes the contribution level (low or high) of a study to the respective DRM stage or RQ.

3.2.3. Research Success Criteria

As DRM [123] suggests, each research study starts with the research clarification activity. The main output from this activity is to define the criteria to judge the outcomes of the research, the success criteria. Success criteria are used to measure the success level of a research project. Despite the prominence and popularity of discussing the success of a research project in academia as a quality indicator, a commonly accepted definition of the research success properties has not been given in the literature [125]. Based on the perspectives of the engaged stakeholders, success can be defined in various ways and by using different attributes of a project. The classic success evaluation approach roots in the three main pillars of the "golden triangle": time, cost and performance [126]. However, the emergence of new success values during the past decades, such as user or stakeholders' satisfaction and sustainability factors, has resulted in the adaptation of additional project properties to measure the success level [125], [126]. Accordingly, based on the objectives of the studies conducted in this PhD project and the methods utilised to conduct the work, specific measurable success criteria were defined that hereinafter will be briefly mentioned. To discuss the success level of the research conducted in this PhD work, in section 5.3, these criteria are referred to.

- *Acceptance by experts* is a common criterion to judge the credibility of the conducted research. The publications that are peer-reviewed by the experts within the field in academia and industry can be used as an evaluation metric.
- *Accuracy of the proposed methods* can be evaluated by comparing the research outcomes with other methods or with reference data or the empirical results using statistical measurements.
- *Generalisability and robustness* are important attributes of high-quality research work. The evaluation can be done in numerous ways, such as judging the validity of the research outcomes when used in cases other than the ones studied, or by measuring variation levels in results.
- *The efficiency of the proposed methods* is another criterion to check the success of the research work. Among other things, efficiency can be measured as the required time to conduct a simulation or design process with a prescribed quality level.
- *Applicability in the industry* is also one of the main success criteria, specifically in research studies like the one presented in this thesis, as the need for initiating this work arose from the automotive industry.

As a reflection on the selected success criteria, *The efficiency of the proposed methods* relates to the time attribute in the "golden triangle" notion, and *Accuracy of the proposed methods* and *Generalisability and robustness* belong to the performance or quality attributes, together forming the classic success evaluation approach. However, the terms *Acceptance by experts* and *Applicability in the industry* can be categorised under the stakeholders' satisfaction or benefit attributes, belonging to the modern viewpoints on the success evaluation. Also, it is noteworthy to mention that enhancing virtual simulation capabilities and supporting the design-concept-related changes in a product development programme naturally contributes to the sustainability terms by reducing physical prototyping, optimised use of material and less energy consumption by avoiding end-of-line and aftermarket reworks. Therefore, it was assumed that the useful and successful outcomes of this work would contribute to improving sustainability in product development.

3.2.4. Data Collection Methods Employed

To develop the S&R framework, a holistic view of the nature of the problem, its generation mechanisms, causes, characteristics and impacts is demanded. Since the study involves different disciplines, various data collection methods have been employed, including:

Literature studies: to get an overall understanding of the available applicable evaluation methods in industry, accessible industrial resources have been studied. Also, to understand the state-of-the-art theories and methods governing the phenomenon of interest and to further develop these methods, relevant scientific resources and available technical data from forums and conferences were reviewed.

Unstructured field studies: since not all the available knowledge within the field was documented, specifically in the industry, unstructured field interviews and field observations were conducted to better understand the status of the evaluation methods.

Questionnaires: during the subjective listening tests, to elicit the users' perceptions, questions of type paired comparison with magnitude estimation were used. In an initial study, printed questionnaires were used. For the latter study, a digital interface was designed to facilitate data collection and compilation as well as to reduce the possible human error risks during data transfer and compilation.

Experimental data: empirical data collection, both from generic material samples in S&R test benches and real car parts and subsystems, form a major part of the data collection process in this study. The data collected was in the form of sound, acceleration, and force signals, in addition to the parameters defining the test conditions. Real car parts were either used as in a subsystem assembly in the subsystem test bench or in the complete trimmed vehicle both in test rigs and in proving grounds. For response signal collection, calibrated devices were always used. Whenever possible, the physical measurements were repeated multiple times to reduce the effect of measurement errors due to uncertainties in the test conditions.

Virtual simulations: result data from virtual simulations were used in studies focussing on methods for virtual simulation as the main data source. Wherever needed and feasible, for model validation and verification of the findings, simulation results were compared against empirical data.

4

RESULTS

The research activities resulted in nine papers and two master thesis reports, out of which six papers are appended in this report. In this section, a S&R cause-and-effect diagram is introduced as one of the results of the studies carried. In addition, the S&R prediction framework in the form of a flowchart is proposed and discussed as the main outcome of this PhD project. Also, this section provides a summary of the motivation, methods and important results connected to each of the respective appended papers. The reader is referred to the appended papers for the complete descriptions of the theory, methods, and results of each work.

4.1. PARAMETERS CONTRIBUTING TO SQUEAK AND RATTLE ANALYSIS

As one of the main objectives of this PhD research work, developing a prediction framework and identifying its main elements has been a central concept of the different studies performed. To achieve this, the contributing parameters and elements to the S&R prediction process, the technical domains they belong to and their relationships were needed to be identified. The main sources of data for devising such a network were literature reviews, accessible industrial resources, field observations and interviews with experts active within the field, as well as the experiments and trials performed for exploring and understanding the phenomenon. This includes, but is not limited to, involvement in the product development activities of running car programmes, from planning and benchmarking activities to analysing the production and aftermarket data; discussions and knowledge transfer with researchers within the field through technical forums and conferences; technical discussions with suppliers of the test equipment and CAE tools; critical review of the current virtual simulation methods and physical evaluation procedures; review of the applicable requirements and the process of requirement setting; reviewing and analysing the accessible lessons-learned reports and the current model quality (CMQ) data. It is of importance to mention that most of these industrial resources were classified as proprietary information giving restrictions on publication. These studies yielded the S&R prediction cause-and-effect diagram as depicted in Figure 14. The diagram is divided into three main domains: system input, modelling and simulation, and assessment criteria. Hereinafter, these domains are introduced in the order reflecting their weights within the studies conducted in this PhD project.

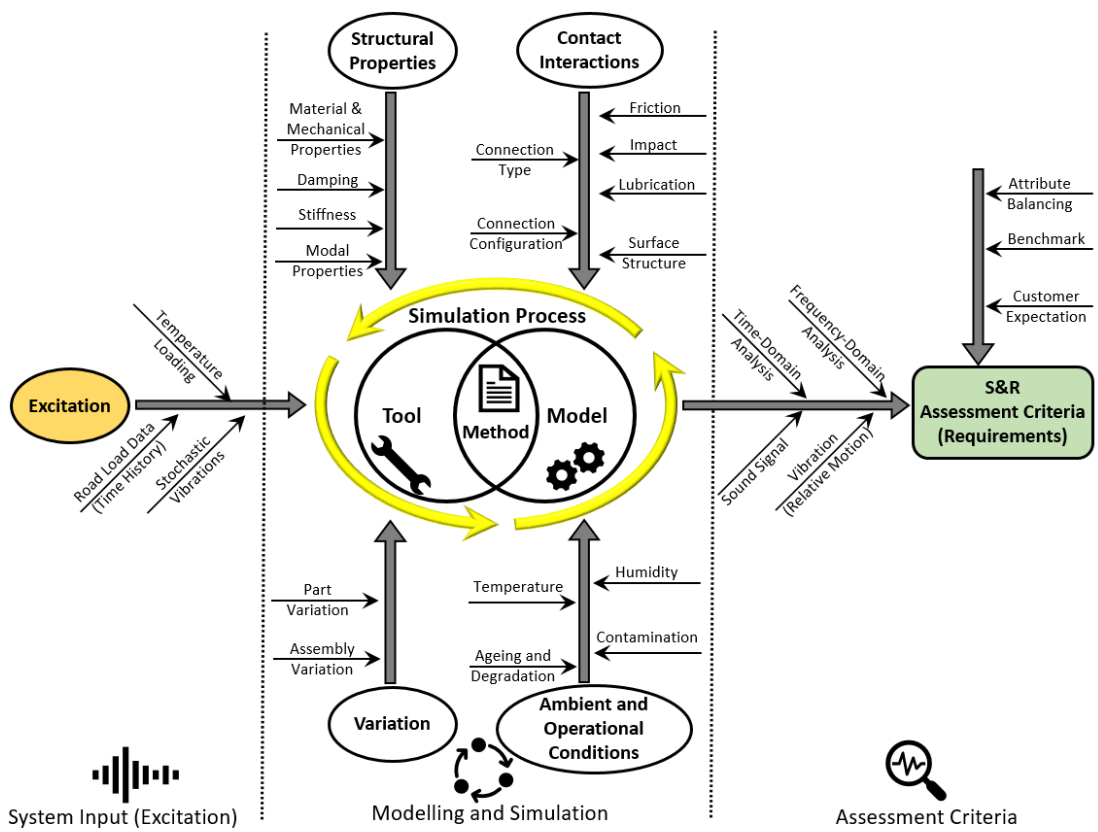


Figure 14: Squeak and rattle cause-and-effect diagram.

Modelling and simulation: This area has formed the core part of this research work. Depending on the simulation process, different contributors can be considered for S&R prediction. Structural properties are important contributors to the generation of S&R. Material and mechanical properties of a part affect the dynamic response and influence the characteristics of the generated sound. The structural dynamic response of a system and the quality of the generated sound can vary due to system damping, its modal properties and mechanical stiffness. The contact interactions and the boundary conditions between neighbouring parts in a physical or virtual model affects its response. The friction and impact parameters in the interfaces between parts change the system dynamic response and affect the quality of the produced sound. Surface conditions and lubrication can also influence the interaction between parts. The connection configuration in an assembly and the type of connectors play an important role in the static and dynamic behaviour of an assembly and, resultantly, the risk for the generation of S&R. The ambient and operational conditions may affect the generation of S&R events while can also contribute to the severity and characteristics of the generated sounds. Ageing and degradation, because of usage under operational conditions, can change both the mechanical and geometrical properties of a part. Humidity, temperature, and contamination can change the surface properties and mechanical characteristics of a part. Temperature changes can also impact the geometrical properties, dimensions, and assembly loads of a part. An important contributor to the generation of S&R is the geometrical variation introduced in different production and usage stages. While part- and assembly-level manufacturing variations can result in geometrical variation in critical interfaces for S&R, operational conditions, such as temperature and ageing, can magnify this risk.

The S&R simulation process involves the three elements: the model, the tool and the method, as illustrated in Figure 14. Some of the important current virtual and physical simulation methods and tools applicable to the prediction of S&R are briefly mentioned in section 2.2. A model can be a physical model, a CAE virtual model or a geometrical virtual representation of the real product in the form of CAD models. Throughout the model development and simulation processes, these models are interrelated. CAE models are often built based on CAD models and are then often validated against physical models. A CAE model can also be built based on the empirical results by parameter identification techniques, such as the low-degree-of-freedom models based on the modal and structural properties of a system. A CAE model can represent the complete vehicle, a subsystem in the car, a single part, or even a portion of a part or subsystem. Based on the purpose of the modelling and simulation, the available resources and the maturity of the CAD models, the CAE models can vary in type and details. In the initial stages of the concept or design phase of the product development process, CAE models can be developed from scratch and may not be based on CAD models. These CAE models are then used as input for generating more mature CAD models. This process can be done recursively. CAD models are also used for building physical models. A physical model can be an exact replication of the final product or can represent some attributes of a product by using simplified or adjusted parts. A physical model needs certain interfaces to be used in a simulation or test process. To define these interfaces and validate the non-exact representative physical models, CAE models can be used as the reference. CAD models are often developed through a gradual evolvement within the product development process. Throughout the development, the maturity level evolves by exchanging the data with CAE and physical models. In the S&R prediction process, apart from the development of CAE and physical models, CAD models are used in contact point analysis (CPA). Based on the CPA results, a decision for the other required types of physical or virtual simulations can be made.

Assessment criteria: When studying an attribute feature of a product, besides the type of system input, model type and simulation and analysis methods, assessment metrics are needed to define the required criteria for the product verification. For S&R prediction, these criteria can be set as objective or subjective requirements. The metrics may need to be adjusted based on the maturity level of the system input, modelling and simulation process and analysis methods. These quantified criteria are used in the requirement setting phase to clarify the product quality. It was an important part of this research work to explore this area to understand the status and identify workflows for improving the existing metrics and defining new assessment criteria. The assessment metrics can be calculated using the data gathered from the physical tests or virtual simulation and analysis. The collected system response can be in the form of sound or vibration signals. The analysis to calculate the metrics can be done in the time domain or the frequency domain. A survey on the previous and state-of-art metrics used for detecting, rating and classifying S&R events is given in section 2.2.2.

System input: The quality and the confidence level of the judgements made through the S&R prediction process also depends on the quality of the system input. By system input, we mean how the system should be excited. Independent of physical or virtual models and employing different simulation and analysis methods, for a robust judgement, the system excitation should ideally cover the whole operational conditions known to be critical for S&R generation. Furthermore, to use the different available modelling and simulation approaches interchangeably, the system input needs to be adjusted for a reliable and repeatable judgement. For instance, in the S&R attribute verification process, a subjective sound analysis using the physical complete vehicle prototypes in the proving ground, or structural dynamic response analysis using the finite element model of a subsystem in the virtual simulation, demand homogenised and level-adjusted system inputs. This was the subject of one of the studies [29] carried out in this PhD project. The reference excitation data can be gathered from the complete vehicle, subsystems of the car, or even parts under operational conditions. The system excitation can be in the form of stochastic or time-history signals defined based on the collected signals under operational conditions. S&R drive file definition and synthesis was a study subject in this PhD project [127]. This data can be transferred between different system levels and the physical and virtual models. One of the operational loadings for S&R simulation is the temperature loading that can change the estimated risk level for the generation and severity of S&R sounds.

4.2. THE OUTLINE OF THE CONDUCTED STUDIES

In Figure 15, the studies that have been conducted in this research are positioned in the three main domains of the S&R cause-and-effect diagram and respecting their contribution to addressing the research questions. The logical tread among these studies can be briefly described as follows. Similar to the previous study on the nonlinear simulation of impact events to predict rattle phenomenon (study A3[90]), study 1 was carried out to investigate the inclusion of friction parameters in the virtual simulation of stick-slip phenomenon and squeak events. To overcome the time efficiency drawback introduced by the increased model and method complexities, the application of a model order reduction method in nonlinear S&R simulation was investigated in study 2. Another approach to address the time efficiency concerns of the S&R simulation and evaluation activities can be the utilisation of time-efficient excitation signals. This was addressed in study 3 by proposing a method for generating inclusive and time-efficient S&R synthesised excitation signals. In order to involve some of the major contributors to S&R generation and severity in the pre-design-freeze activities, studies 4 and 5 were conducted. In study 4, a systematic method was proposed to manage the resonance and mode shape properties of a subsystem using quantified metrics based on the frequency response of the system. To actively involve the geometric variation analysis, as a major contributor, in the design phase of the subsystems of a car, a two-stage optimisation strategy was introduced in study 5 to reduce the S&R risk. The methods and metrics introduced in studies 4 and 5 were utilised to apply design modifications in some industrial applications using a multi-disciplinary optimisation to determine the connection configuration, in study A4, and thickness distribution, in study A1. The current adequacy level of S&R virtual prediction methods to replace physical verifications dictates the need for having robust objective S&R sound quality metrics to be used at subsystem-level or component-level physical tests. In study 6, a subjective listening test method has been proposed to be used for robustly designing S&R sound quality metrics. Studies A2 and A5 were conducted as the basis and preliminary investigations prior to conducting studies 6 and 3. Hereinafter, a concise review of the study goals, methods, main outcomes and industrial and scientific contributions is presented for the main studies conducted during the present PhD project.

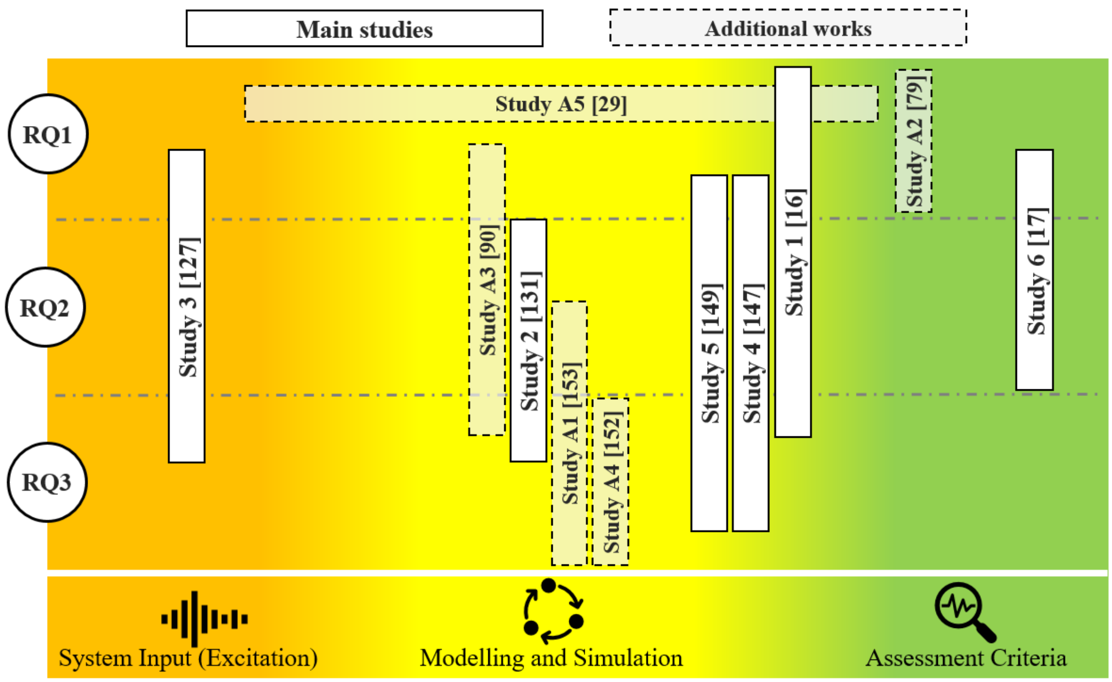


Figure 15: Positioning the studies conducted within this PhD project respecting the study fields and the research questions. The numbers in brackets give the reference number.

4.3. STUDY 1 (PAPER I): EMPIRICAL CHARACTERISATION OF FRICTION PARAMETERS FOR NON-LINEAR STICK-SLIP SIMULATION TO PREDICT THE SEVERITY OF SQUEAK SOUNDS [16]

Background: To enhance the accuracy and robustness of the virtual prediction of S&R sounds in the pre-design-freeze phases of car development, the parameters involved in the mechanisms behind their generation are needed to be included in the modelling and simulation process of S&R events. Squeak is a friction-induced sound that occurs due to improper control of the clearance and relative motion between parts or a selection of incompatible material pairs in the contact interfaces in a car subsystem [6], [128]. Squeak is attributed to the stick-slip phenomenon that is a friction-induced instability at the contact surface. Despite the significant role of friction parameters in analysing stick-slip events [23], virtual simulation and prediction of squeak events lack the sufficient involvement of friction parameters to date [57], [64]–[66], [86], [129], [130]. The main obstacles for this immaturity have been the absence of a universal friction model due to the diversity of the friction-induced problems, the complexity of the mechanisms behind them and the abundance of the contributing parameters [22], [23], besides the computational resource considerations. In this study, friction parameters participated in the nonlinear simulation of stick-slip events to predict the severity of squeak sounds. For this purpose, the variation of friction parameters because of a change in the operational conditions and their relation to squeak risk severity was empirically studied for selected material pairs from the automotive industry.

Method: Although the static and kinetic friction coefficient differences were traditionally counted as the cause of stick-slip events [24], later studies showed the necessity of involving the variation of friction force against the relative velocity in analysing the dynamic instabilities in the stick-slip events [14], [23]. It has been shown that stick-slip instabilities are caused because of the negative slope of the friction force (or friction coefficient) and relative velocity curve [6], [14], [15], [23], [25]–[27]. This effect is referred to as the rate weakening or the Stribeck effect in the literature [22], [23] and is shown in Figure 16(a). In the rate weakening region, by an increase in the relative velocity the friction force reduces resulting in less resistance against the motion acceleration, while the viscous damping deaccelerates the relative motion. This opposing effect and the transition between them may result in friction-induced instabilities. In this work, the rate weakening effect was modelled by an exponential decay function, adopted from [23], as shown in Figure 16(b) and given in equation (2). By an increase in the relative velocity, V_{rel}, the friction coefficient drops from the static friction, μ_s, at zero slip to the minimum kinetic friction coefficient, $\mu_{k,min}$, by a decay factor, d_c.

$$\mu(V_{rel}) = \mu_{k,min} + \left(\mu_s - \mu_{k,min}\right)e^{-d_c|V_{rel}|} . \tag{2}$$

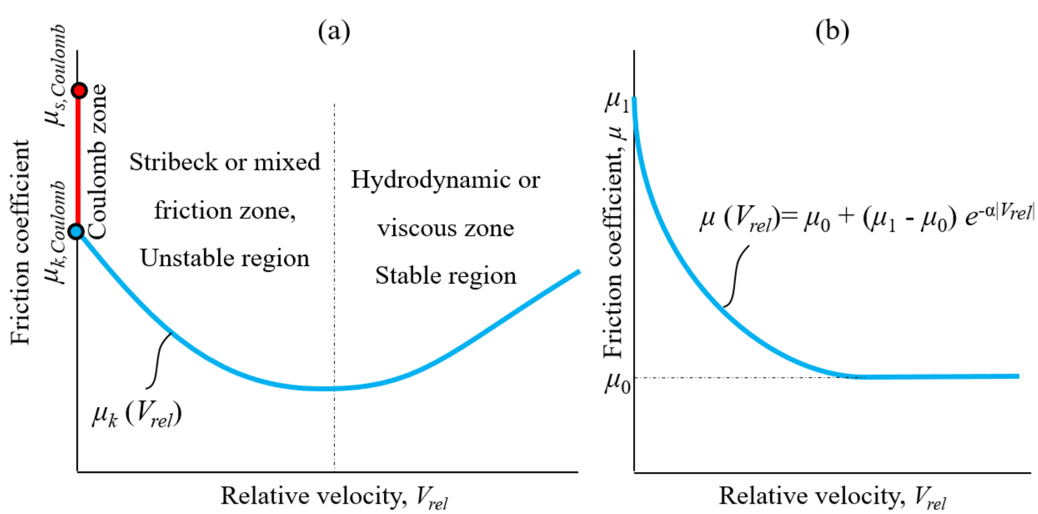


Figure 16: (a) The Coulomb static and kinetic friction coefficients and the rate weakening (Stribeck) and viscous regions. (b) Friction formulation using exponential decay coefficient for the rate weakening region [16].

To study the variation of the static and kinetic friction coefficients and the friction decay coefficient respecting the changes in the normal force and the driving velocity, a set of experiments were done using a translational flexure-based stick-slip test bench [75] shown in Figure 17(a). The experiments were done for a set of metallic and polymeric material pairs, for details see [16]. The testing conditions were defined in two setups: a constant normal load study by varying the driving velocity, V_0 and a constant driving velocity study by varying the normal load, F_n. An FE model of the physical test bench using the model order reduction approach studied in [131] was developed, Figure 17(b). The friction parameters were extracted from the empirical results and used in the FE nonlinear virtual simulation of the stick-slip events to approximate the severity of squeak events. Squeak severity was calculated as a function of the system response parameters of maximum tangential acceleration, the rate of energy dissipation and the periodicity of the stick-slip events and based on the standard output of the stick-slip test bench used in the study [2], [14], [75]. For the details of the test bench and FE model, the experiments and squeak severity calculations see [16].

(a) (b)

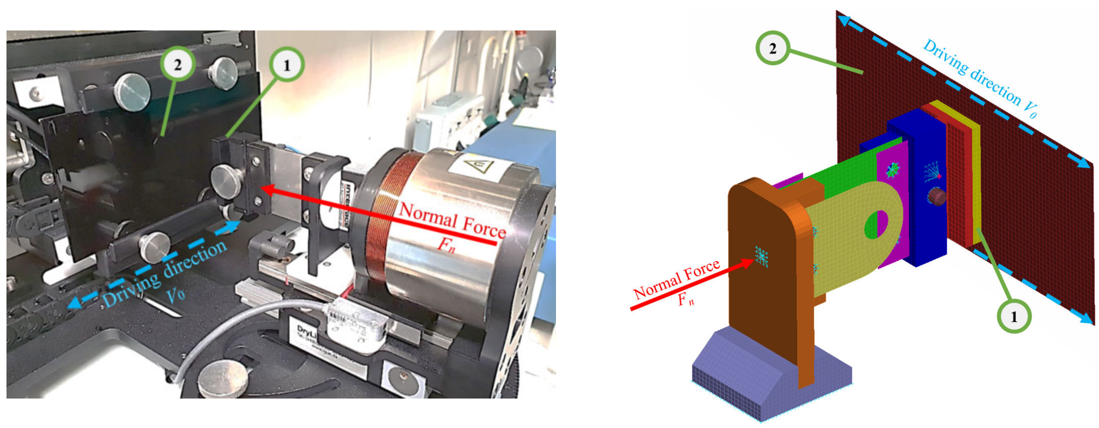


Figure 17: (a) The flexure-based stick-slip test bench (b) Finite element model of the stick-slip test bench with (1) the material sample and (2) the flat board of the counter material [16].

Outcome: In this study, the effect of the negative slope of the friction force vs relative velocity curve was included in the friction modelling using an exponential decay coefficient in nonlinear FE simulation of squeak events. From the FE simulation results, it was concluded that by a proper setup of the friction formula the overall squeak severity could be approximated with low absolute error values of 1.2% to 8.3% for different material pairs. From the empirical results, variations of the friction parameters respecting the changes in normal load and driving velocity and their relationship to the squeak risk severity were investigated. For all material pairs, it was seen that the changes in squeak severity were more influenced by the variations in the static and kinetic friction coefficients difference and the decay coefficient alterations at high and low normal loads, respectively.

It was observed that the friction coefficients and their difference have an exponential relation with the normal load and a linear relation with the driving velocity. Overall, it was also seen that the decay coefficient decreases both with an increase in the normal load at low normal loads and an increase in the driving velocity. These variations indicate a need for updating the friction parameters in virtual simulation models respecting the changes in the operational conditions. It was also shown how a polynomial relationship between the squeak severity risk and the parameters of the operational conditions, equation (3) for instance, can be established, see Figure 18. It was proposed to use these polynomial approximations in linear structural dynamic simulations to estimate the severity of squeak events from the system response.

$$\text{For all material pairs at 40 [N] normal load: } S_s = -0.000\widetilde{V_0}^3 + 0.0108\widetilde{V_0}^2 - 0.0458\widetilde{V_0} + 0.67$$

$$\text{For PP-St material pair at 30 [mm s}^{-1}\text{] driving velocity: } S_s = 0.0001\widetilde{F_n}^3 - 0.0173\widetilde{F_n}^2 + 0.5483\widetilde{F_n} + 4.02 \tag{3}$$

Scientific and industrial contribution: In this study, the variation of friction parameters respecting the changes in the operational conditions and their relation to the severity of the squeak sounds were investigated through empirical experiments. Previously the influence of operational conditions such as normal load, driving velocity, material properties, surface finishing and conditions, ambient effects and dwelling on squeak have been mainly studied for polymeric materials [13], [15], [21], [26], [27], [58], [62]. In this work, the focus was on studying the relationship between the operational conditions and friction parameters for the application in the virtual analysis of stick-slip events. Apart from the friction coefficients that were investigated in previous works [21], [24], [62], the variations of the decay coefficient and its contribution to squeak severity was investigated in this work. It was concluded to define these variations by approximating exponential and linear functions to update the friction formulation during the simulation. From the industrial point of view, material compatibility is one of the provisions to avoid squeak sounds in the automotive industries [2], [4], [6] and the use of stick-slip test results is a standard practice among the car manufacturers [14], [15], [26]. The extraction of friction parameters and specifically the friction decay coefficient from the stick-slip test results as studied in this work can lead to defining approximating functions for these parameters respecting the changes in the operational conditions. This can enhance the virtual prediction accuracy and robustness by employing accurate friction models. It was also proposed that the relationship between the squeak severity and the operational conditions can be approximated by polynomial functions. These functions can be used in the linear structural dynamic analysis, where the driving velocity and normal force in the contact interface can be estimated or approximated by linear models. This may increase the squeak risk prediction robustness in the pre-design-freeze phases of car development by involving the effect of the operational conditions on frictional behaviour in the critical interfaces for S&R.

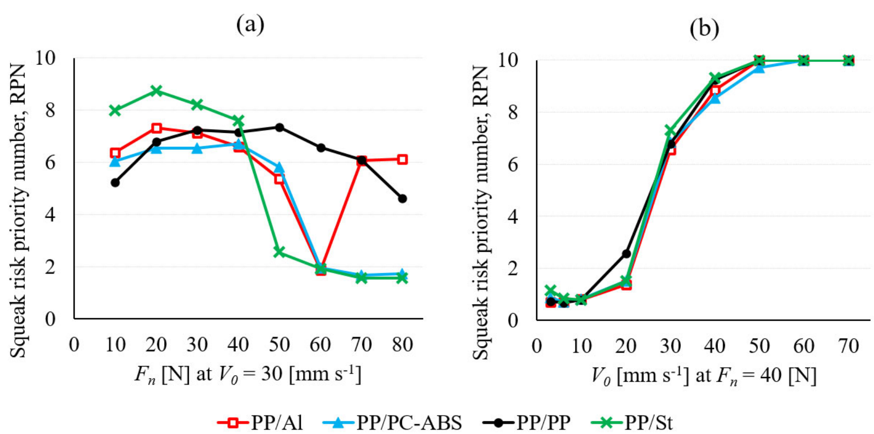


Figure 18: Squeak risk priority number, RPN, for different material pairs versus (a) normal load changes and (b) driving velocity changes in stick-slip experiments.

4.4. STUDY 2 (PAPER II): FINITE ELEMENT MODEL REDUCTION APPLIED TO NONLINEAR IMPACT SIMULATION FOR SQUEAK AND RATTLE PREDICTION [131]

Background: As indicated in the literature [20], [23], [89], [28], [54], [55], [57], [59], [86]–[88], accurate prediction of S&R events depends on accurate prediction of the kinetics and kinematics of the contact events that generate the sound. However, to capture the broadband response for S&R analysis a sufficient resolution of the FE mesh is required and as it was experimented before [20], [85], [90], [91] nonlinear simulation of contact events, even for small components and FE models, is computationally expensive. To further study these phenomena using nonlinear FE models, provisions are needed to be made to make the simulations computationally efficient, without sacrificing quality adequacy. Dynamic substructuring approaches, as first introduced by [132], aim at decomposing the problem into subsystems and solving the smaller models, while data transfer happens at the interfaces of the subsystems. A review and classification of different dynamic substructuring approaches and their relationships was given in [133]. Component Mode Synthesis (CMS) extended substructuring methods by employing Model Order Reduction (MOR) methods [48], [134]–[136] for the substructured models. The Craig-Bampton [135] CMS method has been widely applied to industrial problems for linear complex substructures [137]. Although there have been studies addressing the employment of the Craig-Bampton method in problems with geometric nonlinearities [137]–[141], the application in models with a large number of interface degrees of freedom or when nonlinearities appear in the vicinity of the interfaces was not promising. Thus, the application of the Craig-Bampton method in problems with nonlinearities of contact type remains an interesting subject for research in the structural dynamics field. Exploration of this application was the purpose of this study.

Method: The problem of interest was the nonlinear simulation of the S&R events in a subassembly using the Abaqus solver. The FE model of a side door assembly was obtained and by referring to a digital pre-assembly report [80] and field interviews with analysis engineers the critical interface for the generation of S&R was defined. The original FE model was substructured into linear and nonlinear regions, as depicted in Figure 19(b). The nonlinear region contained the contact interfaces for capturing the dynamics of the S&R events defined based on the guidelines from [90]. The Craig-Bampton method [135] was employed to reduce the linear part of the model. To study the effect of the vicinity of the substructure interface to the nonlinear region and the retained degrees of freedom, the system was substructured and then reduced in different ways, as can be seen in Figure 19(a). The cost of computation was the main parameter to be minimised while quality constraints over the accuracy of the response were defined and monitored for each reduced model. The quality criteria were defined as measures of Modal Assurance Criterion (MAC) [142], frequency response comparison of the nonlinear event using the Normalised Root-Mean-Squared-Error (NRMSE) [143] and the contact time, location and force in the nonlinear event. For details, see [131].

Outcome: The study presented the successful employment of the standard Craig-Bampton method [135] in simulating nonlinear S&R events. The computational time, compared to the original non-reduced model, could be decreased by 98%, while the quality of the dynamic response of the system was maintained by monitoring the defined criteria. By employment of some of the reduced models, a good approximation of the system response was achieved, namely 0.98 and 0.93 for MAC and NRMSE metrics, respectively. While in a few events contact force was estimated with 2.5% to 22% error on average, the location and time of the contact events were captured accurately by the reduced models. As one of the main conclusions from the study, it was shown that the definition of the substructure interfaces closer to the nonlinear region (up to the distance equal to the size of one element) does not negatively influence the system response, while the gain on the computational cost is considerable.

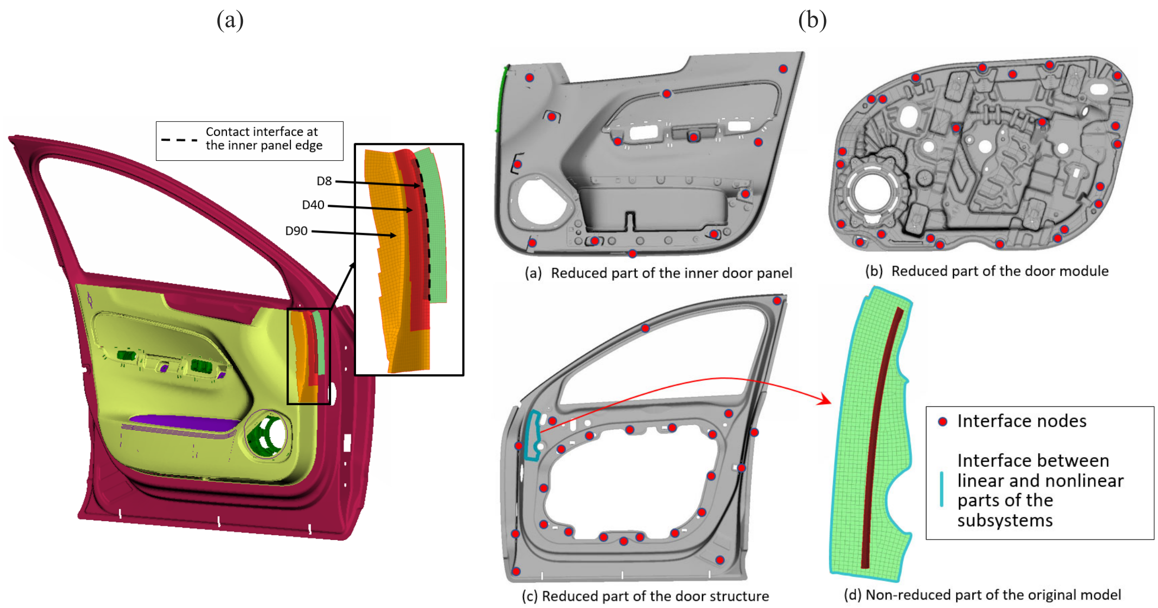


Figure 19: Finite element model of the side door. (a) Different substructure interface definitions (D8, D40 and D90), (b) the reduced linear and non-reduced nonlinear substructures of the side door according to [131].

Scientific and industrial contribution: The main scientific contribution of this study was the exploration made of the employment of the standard Craig-Bampton method [135] in finite element simulation, including contact nonlinearities. The study of how the substructure interface definition influences the response quality, although vital for the application of the method, was not available in the literature. Furthermore, similar to other attempts [137], [144] to implement interface reduction approaches with the Craig-Bampton method, this study was further extended to introduce an interface reduction method based on the system response in terms of S&R criterion that was presented in [145]. As per the industrial application, the use of a CMS method for nonlinear simulation of S&R events, where high accuracy of the dynamics of the contact events is needed, was illustrated in this work. It was shown that a great reduction in computation time could be achieved, measured as a 98% reduction for the studied industrial case [131]. This method was also employed in a later work [16] to investigate the nonlinear simulation of stick-slip events for squeak prediction.

4.5. STUDY 3 (PAPER III): A STRATEGY FOR DEVELOPING AN INCLUSIVE LOAD CASE FOR VERIFICATION OF SQUEAK AND RATTLE NOISES IN THE CAR CABIN [127]

Background: The evaluation of S&R risk and the verification of its status, greatly rely on how the system under study is exposed to disturbances. The driving conditions uncertainties introduced by the human drivers during the physical complete-vehicle-level subjective evaluation, together with the current pressure on employing virtual or physical subsystem-level testing, emphasises the necessity of utilising efficient and inclusive excitation methods. Today, in the industry, the vibration levels at the mounting interfaces of a subsystem or at the position of the wheels of the complete vehicle are collected from physical or virtual proving grounds. To increase the robustness and generalisability, car manufacturers use a range of disturbances, with stochastic profiles, such as Belgian blocks, Vienna blocks, spalled concrete, cobblestone and rough roads, or with frequency-modulated content, such as washboards and rumble strips, or with transient properties, such as potholes, ropes and expansion joints on a smooth road [68]–[70]. This variety in the application comes with the cost of a long processing time. An approach to address this defect is to generate condensed synthesised signals capable of maintaining the main content of the original excitation signals.

A common approach in the automotive industry to develop short excitation signals has been the random vibration control method as reviewed in [72] and its technical considerations were discussed in [68], [69]. The inadequacy of using random vibration control approach for system excitation in representing the time transient events [68], the increased variability in the test results [72] and the reduced prediction accuracy [74] drive the need for developing efficient and accurate time-history excitation signals. However, the technical difficulties in producing such signals have obstructed a wide application of time-history-based excitation for S&R verification [69]. This work dealt with developing efficient and inclusive S&R signals in the time domain by studying the effect of the parameters involved in the signal design and synthesis.

Method: In the previous works concerning S&R drive file generation, the detection of the relevant parts of a reference input signal was based on the frequency or time-domain composition of the input signal [3], [56], [68], [69], [74], [146], and mainly the acceleration peaks, such as in [56], [68], [69], [74]. Nevertheless, in this study, significant parts of the reference input signal were identified respecting the severity of the system response in terms of S&R risk. For this purpose, severity metrics for S&R events (equation (4)) were calculated from the system response in critical interfaces for S&R. These interfaces can be identified based on the available knowledge about the system or the results of the contact point analysis as suggested by Daams [4]. The severity metrics were defined as functions of relative motion of the parts at the S&R interface as detailed in [127].

$$\begin{aligned} S_S(i) &= \bar{x}_n(i) \times \bar{x}_p(i) \times \bar{v}_p(i) \times \left(1 - {}^{\bar{a}_p(i)}/_{k}\right). \\ S_R(i) &= \bar{x}_n(i) \times \bar{v}_n(i) \times \left(1 - {}^{\bar{a}_n(i)}/_{k}\right). \end{aligned} \tag{4}$$

In generating robust S&R excitation signals, in addition to an inclusive selection of reference signals, the selection of important events in each signal and a proper method to merge them into a continuous signal are essential [68], [69]. In this study, this was controlled by introducing some statistical signal design parameters that are illustrated in Figure 20. These parameters included severity threshold, event spacing and event length to determine the significant sections from the response signal and pause and ramp-up duration that were used to compile and merge the equivalent identified sections of the reference excitation signal. For a detailed description of these parameters, see [127].

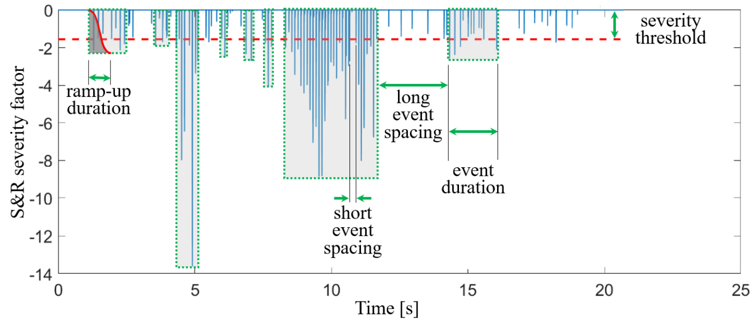
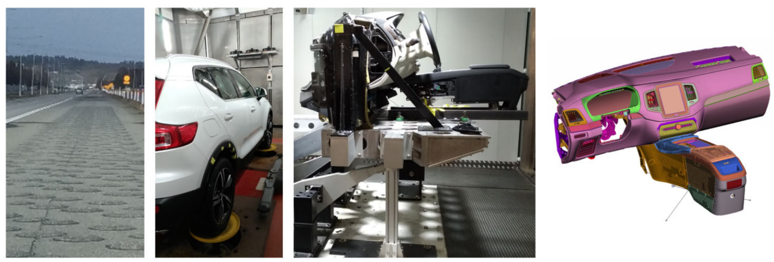


Figure 20: Synthesised S&R design parameters for detecting and merging significant events from the reference excitation signals [127].



(a) (b) (c) (d)

Figure 21: (a) The proving ground for collecting the reference S&R road disturbances, (b) the complete vehicle at the four-poster rig, (c) the instrument panel in the subsystem shaker rig, (d) the FE model of the instrument panel [127].

The proposed method was employed to construct an inclusive S&R input signal for evaluating S&R in an instrument panel of a passenger car. The reference signals were collected from the proving ground, Figure 21(a), for different transient, stochastic and frequency modulated road surfaces. Signal generation was done at the subsystem level and the complete vehicle level to be used in a subsystem shaker rig, Figure 21(b), and a four-poster test rig, Figure 21(c), respectively. For the subsystem level signal generation, the study was conducted using both the empirical data collected from the shaker rig and the simulation results of the corresponding FE model of the system, Figure 21(d).

Outcome: In this study, it was shown that with an appropriate selection of the signal design parameters, inclusive synthesised S&R excitation signals can be generated that comply with efficiency and accuracy requirements. In an industrial application, the proper ranges for these parameters and the quality of the resultant signal by virtual and physical evaluation studies were demonstrated. Also, it was shown that a synthetic signal with a length of about 5% of the duration of the reference signals could be generated while the approximation error for the overall S&R severity metric was kept as low as 17%. It was observed that the use of virtual models in the initial parameter study phase can accelerate the signal generation process. Although the signals generated by the virtual simulation approach agreed with the signals developed based on the physical results in terms of the overall S&R severity metric, the study showed that comparison at the single reference signal or individual event level might reveal some discrepancies. This might indicate the need for careful handling of the virtual simulation approach and the adoption of more detailed models by including nonlinearities. It was also discussed that the frequency composition of the signals can be referred to at the final tuning stages to support the adequacy judgement and increase the accuracy of the results. In another study [147], for the verification of the design changes in a side door assembly, the excitation signal of the subsystem was developed using the proposed approach.

Scientific and industrial contribution: Studying the effect of the parameters involved in the design process of synthetic S&R excitation signals created knowledge about the importance of S&R event detection, selection based on the severity and then merging into an inclusive signal that had scientific value. These involved parameters and their effect on the quality of the constructed signal in terms of S&R severity metrics was investigated through a parameter study. This was achieved by the carried-out tremendous physical experiments at the subsystem level and complete vehicle level supported by the virtual simulation studies.

The newly proposed signal synthesis method for S&R evaluation, as successfully demonstrated in this work, was based on the system response rather than the input signal content. Compared to the common method of random vibration-controlled excitation, the proposed method has the capability of treating all types of disturbances (stochastic, transient and frequency modulated) by incorporating them into an inclusive synthesised signal. The parameter study conducted on the signal design parameters may help to accelerate the synthesised signal development and increase its quality. This method can be employed to construct excitation signals to be used in the physical and virtual prediction and verification of S&R during the car development process. The availability of efficient and robust synthesised S&R excitation signals can lead to increased efficiency in detecting, robustly prioritising and solving the S&R problems at the subsystem level as well as the complete vehicle level analyses, ultimately contributing to shorter product verification and development and enhanced product quality.

4.6. STUDY 4 (PAPER IV): RESONANCE RISK AND MODE SHAPE MANAGEMENT IN THE FREQUENCY DOMAIN TO PREVENT SQUEAK AND RATTLE [147]

Background: Squeak and rattle is the result of mechanical interactions of two adjacent parts at the contact interface. Squeak is a friction-induced sound resulting from the tangential instabilities in the contact interface caused by the stick-slip phenomenon [16] and rattle is an impact sound caused by the conversion of the kinetic energy of the impacting bodies [2], [28]. Besides other measures, constraining the dynamic relative motion of neighbouring parts is one of the main provisions to reduce the S&R risk in the automotive industry [2], [6]. In structural dynamics, this can be achieved by avoiding the resonance phenomenon in the critical interfaces for S&R by the frequency-domain structural analysis. Virtual simulation of S&R in the frequency domain has not been extensively developed and used in the industry. Frequency response of the system in terms of scaled relative displacement was used in [57], [65] to estimate the rattle risk. Fard et al. [82] empirically and virtually studied the occurrence of rattle sounds in seat structure and concluded that by modifying the resonance modes of the system, the severity of the rattle sounds can be controlled in the design stage. In a commercial tool [64], without revealing the details of the theory and calculations, it was claimed that the frequency response function and the time transient response of the system was used for S&R prediction. Park and Choi [66] used the eigenvectors of the system to calculate the displacement in the time domain at each eigenfrequency to study the probabilistic occurrence of rattle sounds. In a recent study, Utzig et al. [86] used the harmonic balance method in the nonlinear virtual simulation of squeak in a car side door and later further improved the method by considering a variable normal contact force [87]. By assuming a harmonic excitation and response, the system response was approximated by the truncated Fourier series using the harmonics of the fundamental frequency. It was discussed that the use of the harmonic balance method in solving the nonlinear stick-slip problems improves the efficiency of the simulation process [86]–[89].

Although the role of resonance properties of the system in reducing the S&R severity was discussed in previous works [57], [59], [65], [82], [83], a systematic method to manage the resonance risk and mode shape similarity at the critical interfaces for S&R has not been introduced. This work aimed to reduce the risk of S&R by introducing some metrics in the frequency domain to manage the resonance risk and mode shape dissimilarity.

Method: To minimise the risk for resonance and mode shape dissimilarity in critical interfaces for S&R, the system response was evaluated in two steps. In the first step, the resonant risk frequencies of the system in the critical interfaces for S&R were identified. In the second step, the mode shapes of the system in the identified resonant frequencies would be analysed for dissimilarity in the S&R interfaces. After the extraction of the eigenmodes, the response of the system to cyclic loads at eigenfrequencies was calculated. To increase the robustness of the response approximation at the eigenfrequencies, some approximation methods are required, such as polynomial regression models to smoothen the response. In this work, the approximated response was calculated by averaging the system response within the half-power bandwidth [148] about each eigenfrequency. Then, the critical resonance events, determined based on the relative displacement of the parts in the critical interfaces for S&R, were graded based on the S&R severity metrics, equation (5). The total resonance risk of the system was then calculated by summing the calculated S&R severity grades in all resonant frequencies and all critical interfaces.

$$\begin{aligned} &\text{Rattle severity factor: } Fr_R(\omega_r) = \bar{x}_n(\omega_r) \times \bar{v}_n(\omega_r)\cdot \\ &\text{Squeak severity factor: } Fr_S(\omega_r) = v_p(\omega_r) \times \bar{x}_n(\omega_r) \times \bar{x}_p(\omega_r)\cdot \end{aligned} \qquad (5)$$

For the mode shape similarity evaluation, the eigenvectors of the system at every resonant frequency were compared by the Modal Assurance Criterion (MAC) correlation factor [142]. The diagonal terms of the MAC matrix were weighted based on the calculated S&R severity factors as introduced in equation (5). For details of the calculation method and the S&R severity factors in equation (5) see [147].

The application of the proposed method in two industrial cases was demonstrated in [147]. The connection configurations in the subsystem assemblies were optimised by using a two-stage optimisation method [149] and the MOGA algorithm [117], [150], [151]. For the details of the FE models and the optimisation setup, see [147]. In this study, the determination of the resonant frequencies was done in a parametric way by calculating percentile levels and the average of the system response over the whole prescribed frequency range and in all critical interfaces. The percentile level and the average factor for different generic geometries were investigated in a parameter study [147] to conclude reasonable values for the industrial cases.

Outcome: In this study, a quantified method was introduced to manage the resonance risk and mode shape dissimilarity in the critical interfaces for S&R by frequency-domain finite element analysis. In the determination of the resonant frequencies and weighting the mode shape dissimilarity factors, quantified S&R metrics were used based on the structural response of the system as the relative motion between the parts in the critical interfaces for S&R. These severity metrics can be updated in future based on the findings from the later studies on the subject, such as the work done on the system response analysis in stick-slip events for squeak sounds. The resultant connection configuration in the demonstrated application in the industrial case [147], was verified through a transient response analysis. The system excitation was done by a synthesised signal generated based on road excitation using the method proposed in [127]. By comparing the baseline design and the optimised design, Figure 22, it was shown that the risk of S&R was reduced by the resultant reduction in the calculated S&R severity factors and the relative displacement values.

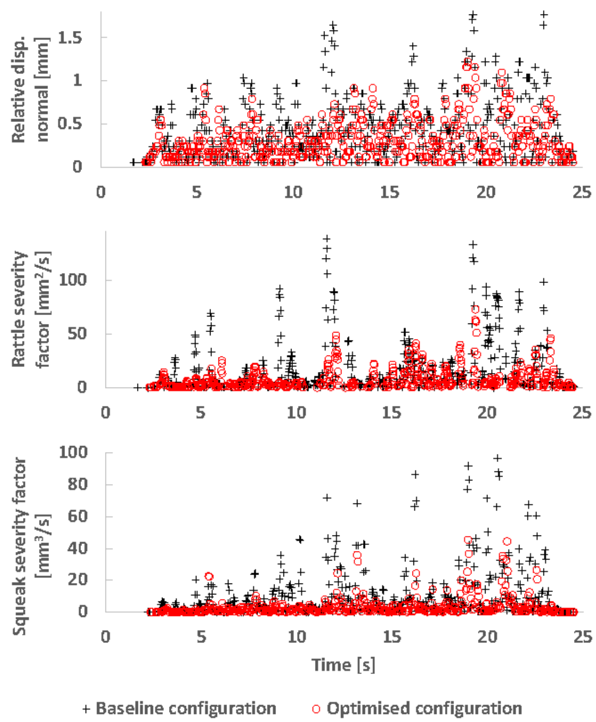


Figure 22: Relative displacement and S&R severity factors at the bottom-right corner of the side door assembly estimated from the system response excited by the synthesised Pave disturbance [147].

Scientific and industrial contribution: As per the scientific contribution, the adopted structural dynamics analysis techniques, half-power damping estimation method and modal assurance criteria factors, and the introduced S&R severity metrics were used to develop a systematic method to reduce the risk of S&R. This was done by managing the resonance phenomenon and the mode shape dissimilarity in a quantified way that enabled the employment of optimisation techniques in the design phase. Based on the parameter study conducted on the percentile and average factor quantifiers in the resonance risk identification method, it was shown that common ranges for these quantifiers can be determined for a variety of geometries and connection configurations. The industrial application of the proposed method was successfully demonstrated in this work. Considering the emphasis of previous studies on the possibility of reducing the risk for S&R, this study proposed a systematic quantified method to manage the resonance risk and the modes shapes in the critical interfaces for S&R. The introduced respective resonance and mode shape objective metrics can facilitate the involvement of S&R evaluation in the attribute balancing during the pre-design-freeze phases to increase the robustness of the design by applying concept-related changes. For the demonstration purpose, the proposed method was used in two multi-disciplinary optimisation problems by involving the dynamic response and the static geometric variations to optimise the connection configuration [152] and determining the thickness distribution [153] in the subsystems of a car.

4.7. STUDY 5 (PAPER V): SQUEAK AND RATTLE PREVENTION BY GEOMETRIC VARIATION MANAGEMENT USING A TWO-STAGE EVOLUTIONARY OPTIMISATION APPROACH [149]

Background: One of the main sources of S&R problems in cars, is geometric variation [2]. The connection configuration or the location of the fasteners in vehicle subsystems contributes to the geometric variation [154] and resultantly in the generation of S&R [2], [4], [93]. The connection configuration refinement in assemblies by geometric variation simulation has been previously researched [94], [112], [113], [154], [155], but with the focus on sheet metal assemblies and the aesthetic properties of the product. Today, the use of geometric variation simulation results in S&R prevention is confined to adjusting the clearance requirements in critical gaps [2], [4], [129]. Nevertheless, the non-rigid geometric variation simulation can be used in closed-loop design procedures to modify the design concept, such as finding the optimum connection configuration in assemblies, or determining the part properties, such as thickness distribution, to reduce the risk for S&R. The main obstacle in this application is the computational cost of such an optimisation process for the large assemblies in a car. In this research, a two-stage optimisation method is proposed to reduce the risk for S&R by optimising the location of connections in an assembly.

Method: The schematic sketch of an assembly of two parts is shown in Figure 23. To make the optimisation process faster, the finite element design space is coarsely discretised for the location of the fasteners. Observation points, called measurement points, are added to the model, where relative variation and deviation between the two parts is monitored. In each measurement point, two measurements are defined: one linear measurement in the direction of the possible impact, namely the rattle direction, and a planar measurement in the normal plane to the rattle direction, namely the squeak plane. Geometric variation, V_i, and geometric deviation, D_i, in the i^{th} measurement point and each direction are defined as:

$$V_i = 6\sqrt{\frac{1}{N_r - 1}\sum_{j=1}^{N_r}\left(d_{j,i} - \mu_i\right)^2}\ , D_i = \mu_i - \mu_{ni}.$$
$$\mu_i = \frac{1}{N_r}\sum_{j=1}^{N_r} d_{j,i}. \tag{6}$$

The objective functions for variation, f^V, and deviation, f^D, are defined as:

$$f^V = \alpha\sqrt{\frac{1}{n}\sum_{i=1}^{n}(V_i)^2} + \max_{i=1\ to\ n}(V_i)$$
$$f^D = \alpha\sqrt{\frac{1}{n}\sum_{i=1}^{n}(D_i)^2} + \max_{i=1\ to\ n}(D_i). \tag{7}$$

These objective metrics can be defined in the rattle direction, $f^{V,R}$ and $f^{D,R}$, and in the squeak plane, $f^{V,S}$ and $f^{D,S}$. For the explanation of terms used in equation (6) and equation (7) refer to [149]. In this work, the variation simulation method used was the Method of Influence Coefficient (MIC) [112]–[114], based on the statistical method of Direct Monte Carlo (DMC) [111], embedded in RD&T software by using the variation model [98] and the point-based method for tolerance analysis [97], [116].

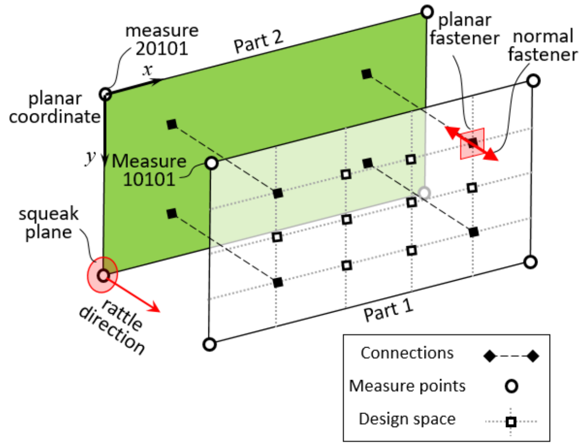


Figure 23: Schematic depiction of the assembly of two parts.

To completely restrain the relative movement of the parts in a large flexible assembly, in addition to the six DOFs for the main positioning system, additional support constraint points are needed to avoid the relative motion of the parts in the normal and planar DOFs due to their flexibility. Finding the location of all these constraints simultaneously makes the optimisation computationally expensive. One provision proposed in this study was to decompose the connection DOFs into two groups based on their function in the assembly: the DOFs with the primary contribution to the measurements in the rattle direction and the DOFs with the primary influence on the measurements in the squeak plane. The optimisation was decoupled into two phases of the rattle direction phase and the squeak plane phase. In the first phase of the optimisation, the location of the fasteners from the rattle direction group was identified by minimising the objective functions in the rattle direction. In this phase, to improve the simulation convergence, a set of planar dummy fasteners were added to the model. In the second phase, to minimise the total variation and deviation, the fasteners from the squeak plane group were placed in some of the connection locations from the optimised configuration from the first stage. In this study, the effect of the order of the fasteners in the assembly process was excluded due to the computational time consideration, similar to [155]. However, this can be investigated in future studies. Accordingly, a sorting constraint was used to reject the equivalent designs respecting the order of the fasteners in the connection configuration.

Decoupling the optimisation into two phases was based on the assumption that the effect of the constraints from the squeak plane group on the rattle direction measurements has a lower-order effect, compared to the effect of constraints from the rattle direction group. This assumption was falsified for a set of generic assemblies with simplified geometries and various connection concepts, based on the common large assemblies in the car cabin prone to S&R problems. The results of the geometric variation analyses were compared for the designs with and without the dummy fasteners using the mean absolute error (MAE) in percentage and the normalised standard deviation (NSTD) in Table 1. Results indicated that the assumption proved to be valid in most of the cases studied. A proposal to treat the cases with similar effect orders between the rattle direction group and the squeak plane group was to consider a weighting factor for the objective metrics of variation and deviation in the optimisation process based on the calculated MAE/NSTD ratios.

Table 1: Variation and deviation results for the simplified geometries with and without including the dummy fasteners [149].

Objective function	%	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6
$f^{V,R}$	MAE Diff.*	24	47	12	3	7	0
	NSTD**	44	97	30	33	31	20
	MAE/NSTD	55	48	40	9	23	0
$f^{D,R}$	MAE Diff.	34	58	29	43	6	80
	NSTD	56	144	68	35	40	30
	MAE/NSTD	61	40	43	123	15	267
$f^{V,S}$	MAE Diff.	569	71	90	623	47	0
	NSTD	50	10	12	1	12	21
	MAE/NSTD	1138	710	750	62300	392	0
$f^{D,S}$	MAE Diff.	453	67	48	626	41.3	148
	NSTD	42	8	19	3	12	19
	MAE/NSTD	1079	838	253	20867	344	779

* MAE Diff. is the difference percentage of mean absolute error for inclusion and exclusion of the dummy fasteners.
** NSTD is the normalised standard deviation in percentage.

The optimisation method employed in this work was the Multi-Objective Genetic Algorithm (MOGA) [117], [150], [151] using an elite pool. The presence of the sorting constraint resulted in the inefficiency of using the available DOE generating algorithms to construct an inclusive starting population for the optimisation process. To address this problem, a rule-based stochastic DOE generating algorithm by embedding the optimisation constraints inside the algorithm was developed. This method can be categorised under the DOE space-filling approaches [156]–[159] and aims at improving the global search by minimising the bias in the initial population and uniformly spreading the DOE designs that satisfy the constraints. The proposed optimisation method was successfully used [149] to optimise the connection configuration in two industrial cases to reduce the S&R risk by minimizing the geometric variation in the critical interfaces. For the details of the methods, algorithms, variables, models and results of the industrial applications see [149].

Outcome: The main outcome of this work was the developed framework for the optimisation of connectors configuration in an assembly with the aim of minimising the risk for the generation of S&R in critical interfaces by limiting the geometric variation. The study performed on the generic simplified geometries supported the validity of the assumption for decoupling the optimisation process respecting the proposed geometric variation objective. For the geometric deviation objective, the assumption holds true for most of the cases. However, for some geometrical categories, it was observed that the effect of constraints from the squeak plane group had the same order as the constraints from the rattle direction group. By employing the proposed method, the most robust designs respecting the geometric variation and tolerance propagation in critical interfaces can be found. The method was used to find the connection configuration for a side door inner panel assembly and a decorative panel assembly in the instrument panel of a passenger car. For details of the optimisation workflow and the model setup please refer to [149]. In both cases, designs were achieved that performed better compared to the baseline design, considering the geometric variation and tolerance stack-up in the selected critical interfaces for S&R.

Scientific and industrial contribution: The main scientific contribution of this research was the descriptive study done on the assumption for decoupling the constraints in two groups affecting the geometric variation results in the rattle direction and the squeak plane and the involvement of them in the stepwise optimisation. The falsification of the hypothesis and the suggestion to weigh the variation and deviation metrics based on the error-to-response-variation ratio supported the validity of the method. In addition, to overcome the inefficiency of using the available DOE generating algorithms in satisfying the problem constraints, a rule-based stochastic DOE generating algorithm was developed by including the optimisation constraints in the algorithm. The main industrial application of this work was the proposed optimisation framework to reduce the risk for S&R by geometrical variation management. The application of the method for two industrial assemblies was demonstrated and the details for the optimisation setup were discussed [149]. This can facilitate the active involvement of geometric variation simulation, as one of the main contributors to S&R generation, in the design phase of the subsystems of cars. The proposed optimisation approach was also used in other studies to optimise the connection configuration to reduce the risk for S&R by changing the dynamic response of the system [147] or in a multi-disciplinary optimisation [152]. It was also used in another work to improve the design respecting the risk for S&R by the topometry optimisation approach [153].

4.8. STUDY 6 (PAPER VI): ANALYSIS OF SOUND CHARACTERISTICS TO DESIGN AN ANNOYANCE METRIC FOR RATTLE SOUNDS IN THE AUTOMOTIVE INDUSTRY [17]

Background: To enhance the treatment of S&R sounds in the product development process, similar to other types of sounds inside the car cabin [36], [37], the need for having robust objective metrics was identified by literature studies as is briefed in section 2.2.2. By referring to the literature [10], [35], [40], [41], [43], [44], [47], [48] and based on the studies done before [29], [79], it was concluded that to have an objective metric to evaluate the severity of S&R sounds besides their detection, the use of standard psychoacoustic metrics, without considering the temporal properties of the sound is inadequate. This research work further explored the characteristics of rattle sounds to be employed in the objective metrics. Also, in a previous study [79], it was observed that the design of the subjective listening test method impacted the accuracy of the resultant metric. Therefore, it was decided to extend the work by investigating a robust listening test method to increase the accuracy and confidence level of the process for designing S&R objective sound quality metrics in the industry.

Method: To elicit the users' perception of annoyance when exposed to rattle sounds, a subjective listening test was conducted. The test condition was designed such that it represented the real in-cabin condition as closely as possible. The tests were done inside the car cabin and the sound stimuli were played back using calibrated open headphones. The digital user interface for conducting the test was designed to accord the specific needs for collecting the relevant details of the subjects' responses. Sound stimuli used in the test were produced in the laboratory, using the apparatus built during the previous study [79], [160]. The selection of sounds was made to assure the dependent and independent variation of the involved acoustic measures in the study, within the range identified in another previous study [29]. The subjective test method was an adjusted version of the paired comparison method with magnitude estimation [77], [78]. The drawbacks of the method were attempted to be overcome by insights from unbounded response rating and semantic differential methods [77]. The results of the listening test were used in a stepwise nonlinear regression problem to define a sound quality metric for the rattle sounds.

Outcome: The method for designing an objective sound quality metric for S&R sounds was the main outcome of this work. The efficiency and accuracy of the proposed subjective test method were evaluated based on the data retrieved from the interviews with the subjects and their performance during the test. By calculating the objective measures from the test results, the interquartile values for self-consistency and concordance [17] were between 66% to 77% and 77% and 88%, respectively as shown in Figure 24. For the hard task of judging the annoyance level of impulsive sounds, for both expert and standard users, these high ranges imply the robustness and accuracy of the method used. Also, the task was judged to be slightly difficult and most of the subjects claimed that they could keep the judgement consistent throughout the test.

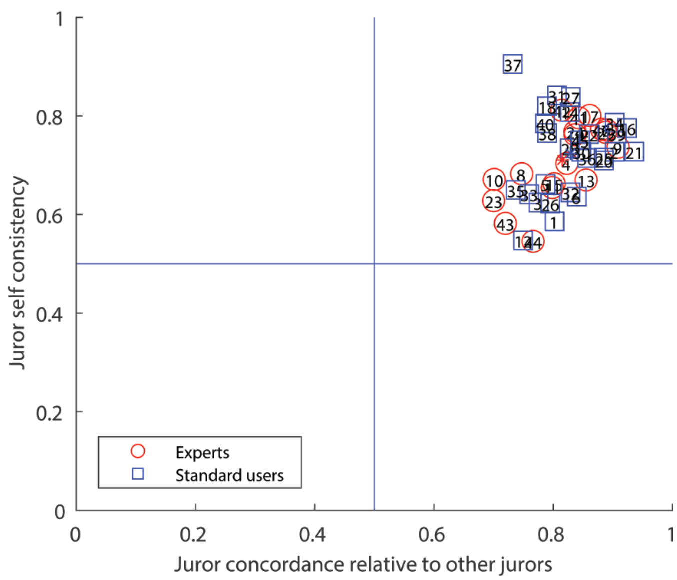


Figure 24: Jurors' self-consistency vs concordance relative to other jurors, with 1.0 denoting 100% consistency/concordance [17].

In addition, introducing different groups of sounds into the design of the listening test, each targeting specific variables in the study, facilitated the use of a stepwise regression method. The inclusion and exclusion of different variables could then be partially independently studied. In addition to the proposed method, the results were used to design a rattle annoyance metric by incorporating psychoacoustic metrics and statistical measures of the sound signal. The predicted and observed annoyance levels for the sound stimuli are shown in the plot in Figure 25. The root-mean-squared error of the prediction compared to the observed perceived annoyance was 0.0479, with a coefficient of determination (R-squared) value of 0.929. This together with the prediction and observation confidence intervals [161] reflected the quality of the fit and the accuracy of the proposed annoyance metric. However, to examine the validity of the proposed metric, recorded sounds from the car cabin should be used in a subject listening test to further evaluate its robustness and validity. This remains a subject for future work in the application of the designed metric in the industry.

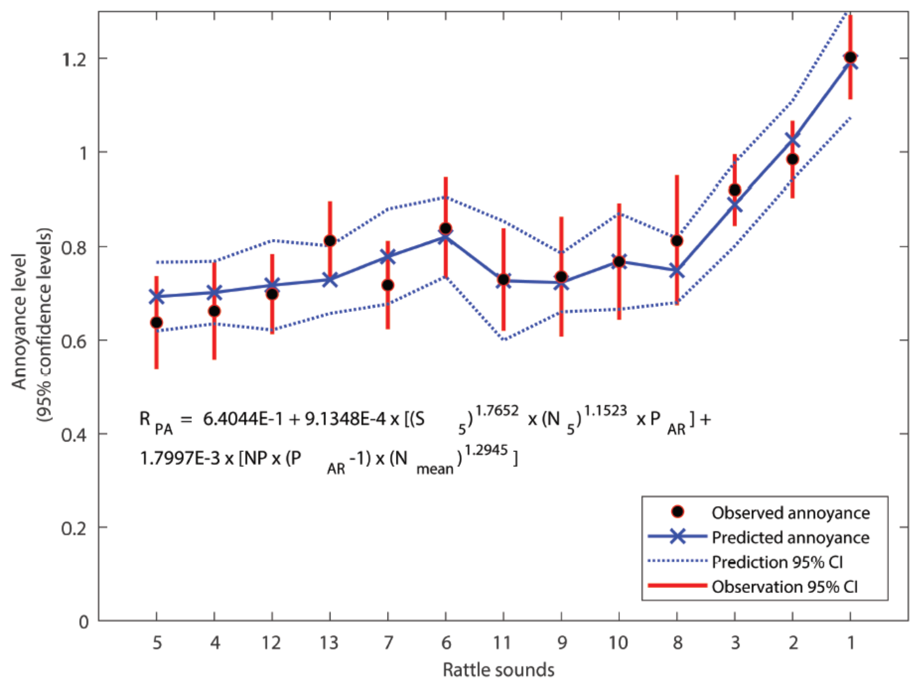


Figure 25: Observed and predicted annoyance levels [17].

Scientific and industrial contribution: This study scientifically contributes to further improving the setup of the subjective listening tests by proposing a new method for subjective testing. It builds upon the existing method of paired comparison with magnitude estimation and suggests provisions to suppress the drawbacks of the method. Further, it introduces the new statistical metric of average relative prominence to be used as a correction factor for psychoacoustic metrics and time-dependent characteristics of impulsive sounds, such as rattle. As per the industrial application, this work gives detailed instructions for planning, conducting, and analysing the results of a robust subjective listening test in the automotive industry. In addition, a new annoyance metric for the evaluation of rattle sounds was proposed in this work.

4.9. THE PROPOSED SQUEAK AND RATTLE PREDICTION FRAMEWORK

As described in section 2.2.2, the methods for detection, severity rating and classification of S&R sounds were discretely mentioned in few publications, such as [2], [6], [10], [20], [33], [57], [64]. Although some methods for the detection and severity rating of S&R sounds were previously presented in the literature, as reviewed in section 2.2 and listed in the reference list of this thesis, yet a systematic S&R prediction process to involve different virtual and physical simulation models respecting their maturity levels, methods concerning their accuracy and efficiency and assessment measures based on the type of results is missing in the industry. One of the objectives in this PhD research was to devise such a framework that encompasses different models and methods by a gradual evolvement of the simulation, prediction and severity rating accuracy and efficiency. The contributors to the S&R prediction process, are presented in the cause-and-effect diagram shown in Figure 14. With the same domain categorisation as in the cause-and-effect diagram, the proposed S&R prediction framework consists of the three main domains of modelling and simulation, assessment criteria and system input, as described in section 4.1. The proposed S&R prediction framework is presented in a flowchart format in Figure 26. The activities are divided into three main levels: the initial global screening, the local high-efficiency low-fidelity evaluation and lastly, the low-efficiency high-fidelity evaluation at critical interfaces. The activities at each level, involve an input definition, model setup, analysis and judgement based on the assessment criteria.

The process starts by performing an engineering judgement using the CPA as described in section 2.2.4.1. The required model for this stage is 3D CAD models and depending on their maturity level, the analysis outcome and accuracy can vary. In this phase, the goal is to identify the high-risk parts, subsystems, or interactions between them through a fast global screening of the whole car or its large systems based on the engineering judgement of the analysis engineers. This process can be semi-automated by identifying the interfaces with contact or small clearance in an automatic search to be submitted for further in-depth CPA analysis.

The second phase of the prediction process encompass simulation and evaluation activities that are computationally efficient, but at the cost of reduced accuracy. Based on the results of the CPA analysis, the identified potential risks can be subject to physical and virtual S&R analysis. The complexity of the problem, the availability of physical prototypes and the analysis time are the definitive factors in determining the type of analysis, to be physical or virtual. In the case of subsystem-level or part-level physical evaluation, system input can be determined by synthesised signals. A method for developing such signals by maintaining the adequacy level of the produced signals was presented in study 3 [127]. Also, to assess the analysis outcomes, objective S&R severity metrics can be used, such as the rattle severity metric developed in study 6 [17], or other sound quality metrics for S&R that can be defined by the method proposed in study 6 [17]. For carrying out the subsystem-level physical testing, the confidence level of the results can be considered by referring to the findings of study A5 [29]. The virtual analysis in this phase includes linear structural dynamics analysis for detection and severity approximation of S&R events. The simulation models are FE mesh developed based on the CAD models. The system input can be defined as the synthesised signals as introduced in study 3 [127] or frequency-domain loadings with an equivalent frequency content. Simulations involve linear transient analysis or frequency response analysis. The system response in terms of displacement, velocity and acceleration can be used to detect the S&R events and to estimate their severity by approximating metrics, such as the squeak severity metrics for linear analysis proposed in study 1 [16], or the severity metrics used in study 3 [127] and study 4 [147], or other severity metrics that were used in previous works as reviewed in section 2.2.2. If S&R events are detected in this phase, based on the estimated severity level, the problems can be subject to design modification activities for high-severity events, or further risk evaluation analysis for low-severity events. In this stage, the design modifications can be carried out by optimisation methods by involving the contributing factors from the cause-and-effect diagram, such as geometric variation analysis as involved in study 5 [149] and structural dynamics properties as in study 4 [147]. Examples of the application of multi-disciplinary optimisation techniques for connection configuration, study A4 [152] and topometry optimisation, study A1 [153], were demonstrated in this PhD project.

In the case of a borderline or low-risk-level S&R estimation in the second phase, the detected events can be submitted for more accurate analyses. These analyses demand detailed models and high computational time and belong to the third level of the prediction framework, the low-efficiency high-fidelity evaluation at critical interfaces. Because of the high computational costs, this type of analysis can be only afforded for critical interfaces that are filtered from the linear analysis. System input can be synthesised signals and the input signal length has a great impact on the efficiency of the method. Thus, implementing inclusive signal generation methods is crucial in nonlinear analysis, such as the method investigated in study A1 [153]. The nonlinearities might involve contact formulation to capture the impact dynamics, as in study A3 [90] and friction-induced instabilities, as in study 1 [16]. For an accurate S&R prediction, the model details and parameters are needed to be defined or upgraded. For instance, the friction parameters required in the friction formulation are needed to be extracted from the material-level empirical data, as experimented in study 1 [16]. To partially compensate for the longer simulation time in nonlinear explicit simulations, model order reduction methods can be implemented in nonlinear structural dynamics analysis, as was investigated in study 2 [131]. Alternatively, other approximating simulation approaches to capture the nonlinear behaviour of the system can be employed as well [19], [84]–[87], as reviewed in section 2.2.4.2. Selecting a proper approach might demand a prior evaluation of the accuracy and modelling-/computation cost balance. Similar to the assessment criteria for linear simulations, the assessment of the nonlinear structural dynamic simulations can be done based on the predicted system response, as the severity metric employed in study 1 [16] for squeak events or the other objective metrics from the literature, such as the approximated sound intensity using the Rayleigh integral method [2], [54], [55] or contact dynamics parameters as reviewed in section 2.2.2. The identified S&R risks can be submitted for design modification to address the problem, with the same approach as described earlier in this section.

The research carried out during this PhD project did not involve virtual acoustic simulation as mentioned in delimitations section 1.2.4. However, based on the S&R risk assessment from the structural dynamics analysis, the borderline or low-risk S&R events can be submitted for acoustic simulation, as also concluded by Kreppold [57]. Such analysis might be done by FEM, boundary elements or statistical energy analysis as suggested by Shorter et al. [20].

It should be stated that the proposed framework, does not cover and involve all the identified elements from the cause-and-effect diagram, due to the limitations mentioned in section 1.2.4. However, the proposed process in the S&R prediction framework can be used as the backbone of the S&R prediction activities. Later, the other contributing factors can be added to the process based on the maturity of the methods and models, availability of the data and simulation resources, and the required level of accuracy in the results. Within the system input domain, the work regarding increasing the efficiency of the system input, study 3 [127], only involved dynamic loads within the time domain and did not include other types of operational loads, such as the temperature loads or the loads due to geometric variation (though the effect of it was considered in some of the studies in this PhD project [29], [149], [152]). Apart from geometric variation, connection configuration, friction and impact dynamics, the effect of some of the contributing factors on modelling and physical and virtual simulation of S&R was studied, such as the ambient conditions and temperature effects, study A2 [79] and study A5 [29], material properties, study 1 [16], study 6 [17], study A2 [79] and study A3 [90]. Nevertheless, to include them in the prediction flowchart, more in-depth investigations are required to study the causal relationship between these elements and S&R events and to formulate these relationships in the form of mathematical representations. Some other elements from the modelling and simulation domain were not involved in the studies conducted, such as ageing and degradation, lubrication, connection types and acoustic simulation. As stated in section 1.2.4., the selection of the study subjects was based on their contribution significance in the formation of the prediction framework, importance as cited in the literature and simplicity and availability of the simulation techniques. Within the assessment criteria domain, the method proposed for designing sound quality metrics for S&R was used to develop a rattle severity metric, study 6 [17]. The same approach can be used to design a squeak severity metric that was not conducted during this PhD project. Also, for the S&R severity metrics based on the contact dynamics, a similar study to what was carried out for squeak events, study 1 [16], is required to be conducted for rattle events. The thresholds for the metrics utilised in the studies conducted or proposed to be used for evaluating S&R events are required to be identified or further fine-tuned through industrial investigations.

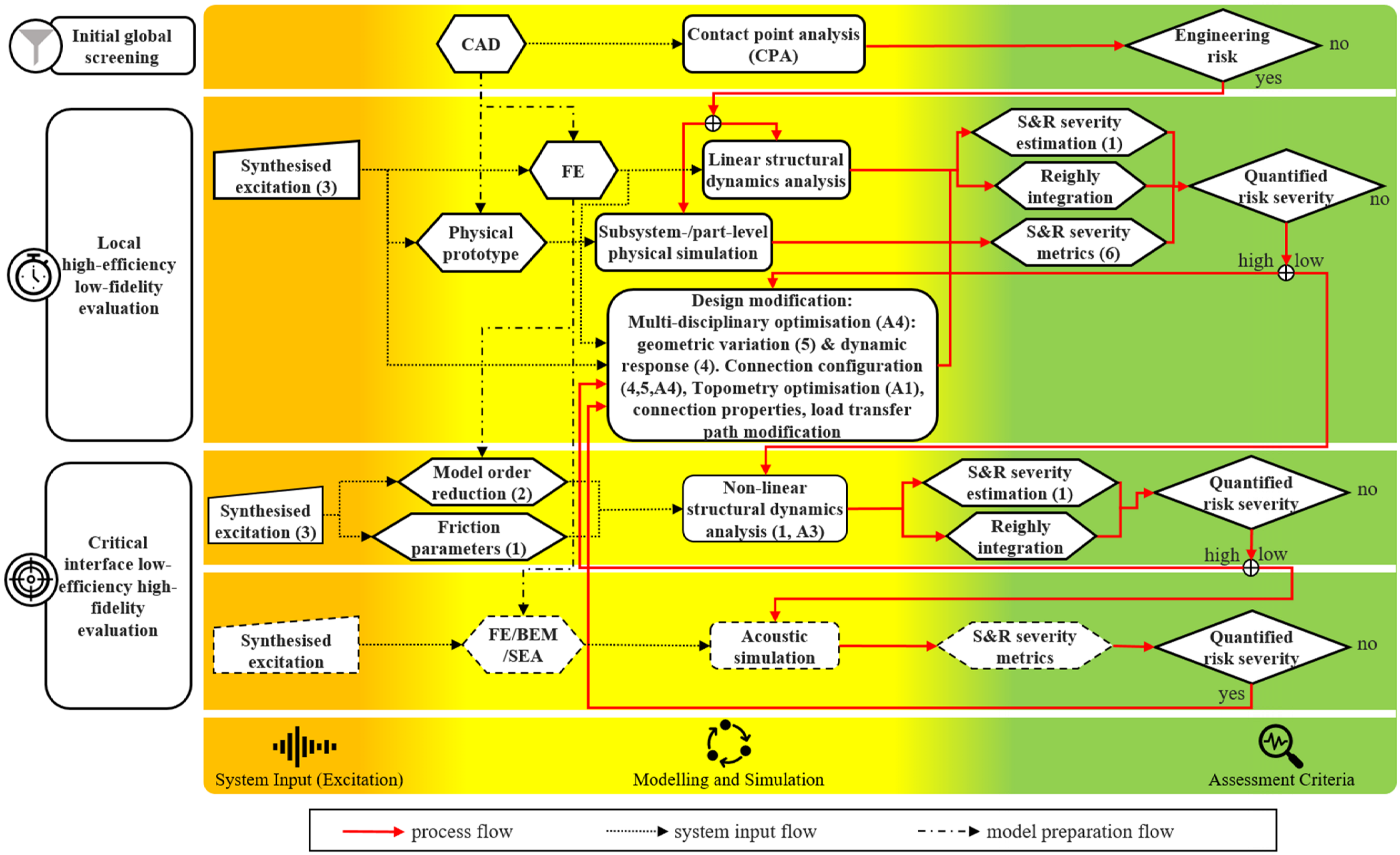


Figure 26: Squeak and rattle prediction framework. The numbers in parentheses give the corresponding study number conducted in this PhD research that can be retrieved from Figure 15 and sections 4.3 to 4.8.

5

DISCUSSION

In this chapter, the research questions are answered by referring to the outcomes of the studies presented in the results section. The contribution of the outcomes to scientific knowledge and their industrial application are summarised. The quality of the presented work is also discussed by referring to the validation and verification criteria.

5.1. ANSWERING THE RESEARCH QUESTIONS

RQ1: *To objectively evaluate squeak and rattle sounds, what elements are needed to establish a robust prediction framework?*

All the literature studies and field studies in this PhD project have yielded the S&R prediction framework, presented in the flowchart of Figure 26. Also, the S&R cause-and-effect diagram shown in Figure 14, introduces the essential elements that are needed to be considered as contributors to the prediction of S&R in the automotive industry. The three main domains encompassing the S&R prediction activities were identified as the system input definition, the modelling and simulation, and the assessment criteria. These domains are discussed in section 4.1 and the identified contributors to each element are given in Figure 14. The modelling process and the interaction between different virtual and physical models are discussed in section 4.1.

Available methods and tools for the virtual and physical prediction of S&R are reviewed in sections 2.2.3 and 2.2.4. Some of the contributing elements to the modelling and simulation domain were studied during this PhD project, such as geometric variation in studies 5, A1 and A4, connection configuration in studies 4, 5 and A4, ambient conditions in studies A2 and A5, friction parameters in study 1, impact event parameters in study A3, structural stiffness in studies 4 and A1 and modal properties in studies 4 and A4. The assessment criteria for the detection, severity rating and classification of S&R events are reviewed in section 2.2.2. The S&R sound-based assessment criteria were investigated in studies 6, A2 and A5 and the assessment criteria based on the structural dynamics parameters were surveyed in studies 1, 3, 4 and A3. Different methods used for defining the system excitation in S&R evaluation activities was reviewed in study 3 and section 2.2.3.1.

The activities involved in the S&R prediction flowchart, presented in Figure 26, are categorised into three different levels: the initial global screening, the local high-efficiency low-fidelity evaluation, and the low-efficiency high-fidelity evaluation at critical interfaces. The activities involved in each of these levels are discussed in section 4.9. Although the proposed S&R framework does not involve all the elements from the S&R cause-and-effect diagram, it can be used as a backbone for the activities required in S&R prediction. In future, based upon the availability of the modelling data and resources and the maturity of simulation methods, these elements can be involved in the prediction process to meet the required prediction accuracy.

RQ2: *How to improve the currently available tools and methods for including the elements involved in the squeak and rattle prediction framework?*

The identified S&R cause-and-effect diagram involves contributing elements from different domains and disciplines. As stated in the delimitations section (1.2.4), it was impractical to cover all these contributors within the scope of a single PhD project. However, an attempt to explore some of these contributing elements and further develop methods for involving them in the prediction process has been made. In this respect, greater attention was given to elements that would support the establishment of a foundation for the S&R prediction framework, as presented in Figure 26.

Regarding the assessment criteria, an enhanced method for designing sound quality metrics for the evaluation of S&R sounds was described in study 6. Also, a sound quality metric by employing new statistical measures to better capture the perceived annoyance level of rattle sounds was introduced in this work. Study 5 proposes objective measures for quantifying the geometric variation simulation results in the prediction of S&R problems. The parameter study conducted for friction-induced events, study 1, and impact events, study A3, describes the best correlating output parameters, with reference to the experimental data, to be used in future for dynamic response metrics in virtual simulations. In study 1, it was also shown and proposed to identify a polynomial relation between the system response parameters and the severity of squeak sounds to be used in linear structural dynamic simulations for S&R prediction. A quantified evaluation metric to measure the resonance risk and mode shape similarity in critical interfaces for S&R was introduced in study 4. For evaluating the quality and adequacy of the excitation signals, objective metrics based on the linear structural response of the system were introduced and utilised in study 3. The available tools and methods for the physical and virtual prediction and treatment of the S&R problems are briefly reviewed in section 2.2. Study 2 describes the employment of a model order reduction approach in the nonlinear simulation of S&R problems. It was shown that simulation cost could be reduced considerably while the quality of the system response could be maintained at an acceptable level. Study 4 presents a quantified method to reduce the S&R risk by minimising the resonance and mode shape dissimilarity by objective metrics calculated from the frequency response of the system. In study 5, an optimisation approach was introduced to optimise the connection configuration in an assembly by actively involving geometric variation analysis in the design phase, as an important contributing factor to S&R generation. The proposed optimisation approach was also used in the multi-disciplinary optimisation context by including the dynamic response and geometric variation to minimise the S&R risk in a connection configuration problem, study A4, and topometry optimisation, study A1. The friction parameters from stick-slip events were the subject of investigation in study 1. It was shown that by involving the rate weakening effect of the friction force curve in the friction formulation the overall severity of the squeak events could be predicted accurately in the virtual simulation of stick-slip events compared to the empirical results. In study A3, the parameters involved in the nonlinear simulation of rattle events and their impact on the accuracy of the results were presented. To increase the efficiency and inclusiveness of the excitation signals used for physical and virtual S&R evaluation, a signal synthesis method in the time domain was proposed in study 3.

RQ3: *How can the proposed framework be used in the new product development process prior to the design-freeze phase?*

The proposed S&R prediction framework in the form of a flowchart gives an insightful guideline for a stepwise evaluation of the S&R status during the pre-design-freeze phases. The prediction activities are conducted through different stages by a gradual increase in the prediction and severity rating accuracy. To address the reduced efficiency respecting the simulation time, a S&R event filtration approach is required to be followed as proposed and described in section 4.9. In implementing the proposed S&R prediction framework in the industry, one important aspect to consider could be the availability of the data and the maturity of the simulation models at different stages of product development. Although this fact was considered in this project while devising the prediction framework, independent studies are needed to investigate the availability of the required data in the prediction process and the robustness of the proposed methods against the accuracy of the available data and models. This was not the focus of the present PhD work due to the time limitations, as it demanded extra research work, firstly, to determine the readiness level of the product data during the product development process and secondly to identify the sensitivity of the prediction results on the accuracy of the input data. For instance, the maturity of the CAD determines the accuracy of the finite element models that would in turn drive the selection of the prediction methods and the accuracy of the simulation results in the proposed prediction framework. Similarly, the availability of the friction parameters, material properties, reference physical or synthesised excitation signals might dictate the adoption of virtual simulation methods with dependable outcomes on the modelling details or system excitation. Also, noteworthy to mention that the availability of the resources is an important driving factor in selecting the prediction method. Indeed, in different stages of the product development process, the allocated resources influence the adoption of different prediction activities to meet the project time goals, either in the traditional stage-gate product development system or the more modern product development systems such as the agile approach. The timing of the different prediction activities in the proposed framework is a variable term that requires continuous adjustments. This variability is caused by various factors such as the continuous advancements in the efficiency of the simulation methods, the enhancement in the computational capacity, and the continuous increase in the modelling and simulation complexity and calculation cost.

The application of some of the methods within the proposed prediction framework was demonstrated in descriptive studies conducted during this PhD project. In study 3, the effect of the variations in parameters involved in generating the synthesised excitation signals was studied for an instrument panel assembly of a passenger car. It was also shown that what set of signal design parameters lead to an effective and inclusive excitation signal in the studied industrial case. The signal synthesis method proposed in study 3 was used to generate an excitation signal for a side door to evaluate and verify the design modifications in an industrial case in study 4.

The model reduction approach employed in study 2 showed the sensitivity of the simulation results to some of the parameters involved in the modelling method. The influence of interface definition between linear and nonlinear parts of the model for a side door assembly of a passenger car and the resulting computation cost gain and response accuracy loss was discussed in this work. In study 5, the proposed optimisation method was employed in the design of the connection configuration of a side door inner panel assembly and a decorative panel assembly in the instrument panel of a passenger car. The same optimisation approach was used in study 4, together with the proposed quantified frequency-domain metrics to manage the resonance risk and mode shape similarity in two industrial applications. The proposed geometric variation metrics, study 5, and frequency response metrics, study 4, were used in a multi-disciplinary optimisation context based on the optimisation approach proposed in study 5 to modify the design concept in some industrial cases to reduce S&R risk. This was conducted for optimising the connection configuration in two industrial cases in study A4 and the topology optimisation of an industrial case in study A1, besides the generic geometries representing the car assemblies in both studies. In these studies, the details of the application of the proposed optimisation method and the modelling and metric calculation details were given and the improvement in the results, compared to the baseline designs, was discussed. In study 1, the dependency of the employed friction model on the operational conditions was demonstrated and it was concluded that a model update regarding friction parameters is required to include these dependencies in an accurate simulation of stick-slip events for industrial applications. It was also shown that the severity of squeak events can be approximated as a function of the operational conditions for different material pairs. Based on this observation, it was proposed to use these approximation representations to effectively estimate the severity of squeak events from the results of the structural dynamics analyses. In study A3, it was discussed that the modelling parameters in nonlinear impact simulation can be used in the model tuning process to improve the accuracy of system response in terms of parameters contributing to the severity of rattle sounds. Study A5 provides a comparative study among different physical S&R evaluation methods by a comprehensive empirical survey through three different test levels. The outcomes of this work can be used to judge the accuracy and adequacy of the laboratory tests compared to the road tests in various driving and ambient conditions.

5.2. SCIENTIFIC AND INDUSTRIAL CONTRIBUTION

The scientific and industrial relevance of the studies conducted in this work is discussed in detail in chapter 4 under each study topic. Overall, the scientific contribution of the studies conducted can be briefed as below:

- The important elements influencing the S&R prediction process were identified and presented in the S&R cause-and-effect diagram in Figure 14.
- The increased knowledge in defining the substructure interface for model order reduction of finite element models and its impact on the accuracy of the S&R simulation results in a nonlinear structural dynamic simulation problem including reduced-order models, in study 2.
- The efficient approach proposed to decouple the identification of the location of the fastener constraints in an assembly into the squeak and rattle coordinates in an optimisation problem and based on the insights generated through the descriptive studies on the dependence of the geometric variation simulation results on the constraints in S&R degrees of freedom. The proposed two-stage optimisation method by implementing this approach and the rule-based stochastic DOE generating algorithm to efficiently form a valid and inclusive starting point in the optimisation process, in study 5.
- The novel systematic method developed to manage the resonance risk and mode shape dissimilarity in assemblies by adopting the half-power damping estimation method and modal assurance criteria factors and utilising S&R severity metrics, in study 4.
- The increased knowledge and understanding of the relationship between the variation of friction parameters in stick-slip events and the operational conditions, and the gained insight about the need for involving these dependencies in the friction formulation in the nonlinear simulation of stick-slip events. The gained knowledge of defining polynomial relationships between the operational conditions and the squeak severity metrics for different material pairs and the proposed approach to utilise these squeak severity approximating functions in linear finite element structural dynamics simulations for the efficient prediction of the squeak risk, in study 1.
- The increased knowledge about the effect of the modelling parameters on the accuracy of the simulation results and the efficiency of the simulation process in the nonlinear finite element simulation of S&R events, in studies 1 and A3.
- The new S&R time-history excitation signal synthesis method proposed based on identifying the relevant sections in the reference excitation signals with reference to the system response in terms of the quantified S&R severity metrics. The knowledge gained about the effect of the important signal synthesis parameters on the quality and efficiency of the constructed signal and the proposed list of reasonable values for the important signal synthesis parameters based on the results produced by implementing the method in an industrial case in study 3.
- The proposed statistical metric of the average relative prominence to be utilised as a correction factor for psychoacoustic metrics and time-dependent characteristics of impulsive sounds to better describe the perceived quality of rattle sounds by the car

users, in study 6.

- The novel subjective listening test method proposed in study 6 to increase the robustness of the sound quality metric development method for S&R sounds as resulted in improving the concordance and consistency of the responses.

The main industrial contributions of this PhD project can be summarised as below:

- The proposed S&R prediction framework in the form of a flowchart, as presented in Figure 26 and described in section 4.9, by involving activities in three different levels based on the accuracy and efficiency of the methods and with elements from the three domains of the system excitation, modelling and simulation, and assessment criteria. The proposed framework can be used as a roadmap of activities for the prediction and severity rating of the S&R events. Although not all elements from the identified cause-and-effect diagram, in Figure 14, were included in the array of elements in the prediction framework, based on the maturity of the methods and availability of the models and resources, they can be embedded in the evaluation process.
- The insight gained by reviewing and categorising different physical and virtual S&R simulation and evaluation methods to be utilised in industrial applications, as reviewed in sections 2.2.3 and 2.2.4.
- The knowledge gained by reviewing and categorising the different detection, severity rating and classification methods, criteria, and metrics, as described in section 2.2.2 to be considered for industrial applications.
- The improvement in the structural dynamics simulation methods by introducing metrics in the frequency domain to manage the resonance risk and mode shape dissimilarity in critical interfaces for S&R, in study 4.
- The utilisation of the geometric variation metrics in the context of a two-stage multi-objective optimisation framework to enable the active involvement of geometric variation analysis in minimising the S&R risk in the design phase, in study 5.
- The demonstration of the application of the proposed optimisation approach and the geometric variation and structural dynamics metrics in a multi-disciplinary optimisation context for concept design modification in some industrial cases, studies A1 and A4.
- The knowledge gained through the empirical study on the friction parameters and the dependency of the squeak severity on the variations of these parameters respecting the operational conditions, as well as the utilisation of a friction formulation in the nonlinear simulation of stick-slip events for squeak event prediction, study 1.
- The investigation on the applicability of a model order reduction approach in S&R nonlinear structural dynamics analysis and the application of the employed approach in an industrial application, study 2.
- The introduction of a robust method for designing sound quality metrics for impulsive sounds like S&R, in study 6.
- The new signal synthesis method proposed to generate inclusive and efficient synthesised S&R excitation signals for physical and virtual S&R evaluation and the demonstration of its application in an industrial case, in study 3.

5.3. REFLECTION ON THE RESEARCH OUTCOMES BASED ON THE SUCCESS CRITERIA

The outcomes of this work, with reference to the prescribed success criteria in section 3.2.3, are briefly reviewed hereinafter.

- *Acceptance by experts*: this criterion is reflected by the number of publications originating from this work as appended to this thesis. The papers have been peer-reviewed by experts within the field, published in scientific journals and presented in relevant conferences and or are under review by pertinent journals.
- *Accuracy of the proposed methods*: this criterion was measured differently in the various studies. In study 3, the adequacy of the synthesised signals was monitored by using statistical measures of the S&R severity metrics and time-related characteristics of the signal, such as the total duration and periodicity of the events. It was shown that by an appropriate selection of the signal design parameters the quality of the synthesised signal could be secured in terms of the adequacy metrics when compared to the reference signals. In study 2, system response after applying the model reduction was compared to the baseline non-reduced model using statistical measurements, including the normalised root-mean-squared error, mean absolute error and modal assurance criterion (MAC). It was concluded that the accuracy of the system response was ensured by monitoring the aforementioned metrics. In study 1, the accuracy of the virtual stick-slip simulations was checked by comparing the estimated squeak severity grade, calculated from the contact dynamics parameters, with the empirical results. For different material pairs, the overall estimated squeak risk severity from the virtual simulations was calculated accurately with the absolute estimation error between 1.2% to 8.3% respecting the empirical results. In studies 4 and 5, it was observed that the proposed optimisation method resulted in optimised designs that outperformed the baseline design concerning the defined variation and deviation objective metrics in study 5 and the resonance risk and mode shape dissimilarity metrics in study 4. This conclusion was made by comparing the objective values for the designs in the scatter plot of the optimisation results. In study 4, the resultant connection configuration was compared to the baseline design respecting the S&R severity metrics and the relative displacement in critical interfaces for S&R, when the system was exposed to a synthetic time-domain excitation. In study 6, the statistical error values between the experimental observations and prediction have been used to calculate the confidence level of the outcome. It was shown that the proposed fit function resulted in accurate predictions within the 95% confidence intervals obtained from the observation data.
- *Generalisability and robustness*: in studies where the study cases were chosen from car subsystems, such as studies 2, 3, 4, 5, A1, A4 and A5, the focus was on the interior subsystems that were reported [2], [6], [12] to be the main origins for the S&R problems, such as instrument panels, door trims and seats that account for about 70% of the S&R events inside the car cabin [2]. Therefore, the findings of these studies are assumed to be valid for a large portion of the S&R problems inside the car cabin. The variation of parameters in the metrics proposed for geometric variation, resonance, and mode shape dissimilarity in studies 4 and 5 was studied for a set of generic geometries. Considering the variety of the studied generic geometries, the selected tuned values for these parameters are assumed to be valid for a broad range of subsystems in the car cabin regarding S&R events. These metrics were used in a multi-disciplinary context in studies A1 and A4 to apply design modifications by

optimising the connection configuration and topometry optimisation in industrial applications. By comparing the resultant designs with the baseline designs, it was shown that the utilisation of the metrics and the optimisation approach yielded successful design concepts. In study 3, a wide range of S&R road profiles, including transient, stochastic and frequency modulated disturbances participated in the signal synthesis process. The adequacy evaluation of the synthesised signals was carried out for different critical interfaces of an instrument panel. These supported the generalisability and robustness of the findings. Also, the effects of the signal design parameters sought to agree between the subsystem level and the four-poster complete vehicle test approaches. In studies where the study subject was a test apparatus, such as studies 1 and 6, it was ensured that the adopted case studies represent mechanisms in the car cabin or the parameters of the test subjects under study were validated against the reference mechanisms in the car. In study 6, the sound stimuli were collected from a rattle producing machine, which was designed in agreement with previous works [17]–[20], under laboratory conditions and in various test setups, to make the study valid for a wide variety of rattle sounds. The structural properties of the test bench were tuned to agree with the characteristics of the common in-cabin components. The selected produced sounds were compared with the cloud of S&R sounds from study A5 respecting the sound quality parameters to ensure that the study covered a wide span of the sounds considering the parameter variations. In study 6, the robustness of the proposed subjective listening test method was examined by calculating quality metrics such as self-consistency and concordance. In study 1, the utilised test bench was a standard translational flexure-based stick-slip test bench with wide acceptance among the automotive experts for studying the squeak events [13]–[16]. The study was conducted for different common material pairs from the car interior subsystems. The test conditions were chosen to agree with the industrial norms based on the operational conditions in the car. Overall, the application of generic virtual and physical models in some of the studies rather supported the generalisation of the outcomes than being a limitation, as the findings were not bound to a specific case and were less influenced by the uncertainties in the modelling and the limitations imposed by the specific setup.

- *The efficiency of the proposed methods*: in study 2, the simulation time was the efficiency criterion and, in comparison to the baseline non-reduced model, the required computational time was reduced drastically, by 98%. In study 3, the objective of the proposed signal synthesis method was to generate efficient and inclusive S&R excitation signals. In the demonstrated industrial case, it was shown that with an appropriate selection of the signal design parameters inclusive synthesised S&R excitation signals with a duration of about 5% of the reference signals could be achieved. The proposed optimisation method in study 5, was affordably utilised in closed-loop design modifications in the industrial cases involving large assemblies demonstrated in studies 4, 5, A1 and A4.

- *Applicability in the industry*: All the studies conducted through this PhD project were designed with a strong emphasis on their industrial application and relevance. The industrial relevance of the findings of these works is briefly listed in section 5.2. In all the conducted descriptive and prescriptive studies included in this thesis, the models were either taken from the automotive industry, such as in studies 2, 3 and A5, or virtual and physical replications of the industrial models, such as in studies 1 and 6, or both, such as in studies 4, 5, A1 and A4. Studies 2, 3, 4, 5, A1 and A4 presented the proposed methods and illustrated their applications in some industrial cases by describing the modelling details and simulation setup. In other studies, a conclusive discussion was given in each of the appended works on the industrial applicability of the proposed methods and outcomes of the work.

5.4. QUALITY OF THE RESEARCH OUTCOMES

Validation and verification might be defined differently when referred to in different contexts. However, in design research, validation is done to check if the product serves the purpose it was intended for. While by verification, one judges the credibility of the outcomes [123], [162].

5.4.1. Verification of the Work Carried Out

As Buur and Anderson [163] proposed, one important fold of checking the research quality is logical verification. Logical verification is about if the implemented approach in the research consistently, completely, and coherently results in falsifying a theory. There shouldn't be conflicting elements within the research and established methods need to be implemented to secure coherency and completeness. All the studies performed in this work lie within the S&R prediction framework depicted in Figure 26. In this PhD research, it was planned to address some of the elements contributing to each of the main three domains in this framework, as given in the cause-and-effect diagram in Figure 14. By using this framework as a high-level description of the problem and by following the DRM research methodology it was attempted to maintain coherency among the different studies. Overall, no conflicting result was observed among the findings of the studies conducted. By referring to the S&R prediction framework, the CPA analysis might lead to conducting physical S&R evaluations if physical prototypes and evaluation methods are available. In such cases, it is important to have objective sound quality metrics to accurately and robustly assess the severity of the events [10], [35]–[37], [40], [41], [43], [44], [47], [48]. The subjective listening test method in study 6 was proposed to overcome the low robustness of the previously utilised methods in study A2 for designing sound quality metrics for S&R. Studies 1 and A3 targeted the nonlinear simulation of S&R events, as the need for having accurate contact dynamics parameters in S&R evaluation was stressed in the literature [20], [23], [89], [28], [54], [55], [57], [59], [86]–[88]. In study 1, the observations made on the friction parameter variations agreed with previous works. The observed drawback of computational inefficiency of using nonlinear simulations in studies 1 and A3, in agreement with previous works, [20], [85], [90], [91], was addressed in studies 2 and 3. In study 2, the adoption of a finite element substructuring method was investigated, while the main objective in study 3 was to generate effective and inclusive S&R excitation signals to reduce the evaluation time. One of the goals of this research was to enhance the S&R prediction capabilities during the pre-design-freeze phases to facilitate the active involvement of its major contributors in the closed-loop design modifications. Geometric variation [2], [4], [6], and resonance phenomenon [57], [59], [65], [82], [83] were identified as two major contributors to the problem at hand, which were not systematically and actively involved in the concept design processes before. In studies 4 and 5 metrics and methods to enable the active involvement of these elements in the design process were proposed. These metrics and methods were successfully used in industrial applications, studies 4, 5, A1 and A4, by multi-objective optimisation techniques to suggest concept design modifications.

5.4.2. Validation of the Findings in This Work

For the research to be valid, it needs to address what it is intended to address. The other fold of the research quality, as Buur and Anderson [163] discussed, is validation by acceptance. The theories and outcomes are needed to be accepted and can be used by the industrial community and the scientific society within the field. The studies conducted were either published or presented in peer-reviewed scientific journals and technical conferences or are under review for publication. The results have been presented at conferences and forums and have been discussed with the experts within the field. Both in planning and conducting the research studies, experts from the industry were involved to ensure the relevance of the work to the needs within the industry. The results of the studies, their industrial application and relevance have been presented and discussed with the relevant stakeholders from the industry and the academic research group.

Winter [164] proposed validation be categorised as internal validity, external validity and construct validity.

- Internal validity deals with the matter that the causes of the outcome are studied correctly. It indicates that the parameters and variables within the boundaries of the study have a causal relationship. In most of the conducted studies, statistical measures were used to compare the results with other available methods or designs. The results were graphically presented in the form of different types of bar charts, contour plots and graphs. For studies 1 and 6, the empirical data were collected under laboratory conditions to have the contributing parameters under control and reduce the uncertainties. When virtual models were used (studies 1, 2, 3, 4, and 5), these were either validated with reference to the experimental data and reference models or already validated virtual models were picked to ensure that the system behaviour was as intended.
- External validity addresses the generalisability of the outcomes of the research beyond the setup of the studies. In the conducted studies, different measures were taken to ensure generalisability, as also discussed in section 5.3. Overall, the industrial case studies were chosen among the most critical subsystems for S&R problems, such as instrument panel, door trims and seats [2], [6], [12]. When specific subsystems were selected to conduct a study, this selection was always based on field studies and interviews with experts to pick a relevant subsystem that could be a good representative of the phenomenon under study. Although in some works the study was confined to a specific subsystem in a car, the conclusions hold true at least for all the subsystems with mechanical properties within the same range. Most of the in-cabin subsystems possess components and connection configurations conceptually similar to the studied cases. In studies 4, 5 and A4, generic representations of the subsystems in a car were used for method development and hypothesis falsification. This makes the findings extendable not only for a wide range of assemblies in the car but also for other products with geometrical assemblies belonging to the studied generic categories. The experimental test apparatus used in studies 1 and 6 had generic designs that complied with the main structural characteristics of the car components. Thus, the problem under study was not limited to a specific part or assembly from a car. Rather, the results and conclusions can be extended to products possessing similar mechanisms. In study 3, the reference signals were picked from different types of road disturbances and the adequacy judgement was done in different interfaces of an instrument panel, which was reported to be the origin of 30-40% of the in-cabin S&R problems [2], [12]. Therefore, the conclusions made are valid over a wide range of S&R problems and road disturbances.
- Construct validity concerns the generalised claims made as the outcome based on the theoretical concepts governing the problem and if the claims relate to the

intended purpose of the research. While checking the construct validity of the research work, the delimitations of the research are therefore the key threatening elements to be considered. In studying S&R problems, special consideration should be taken for different contributing parameters in the phenomenon under study. Otherwise, the authenticity of the outcomes might be endangered. Using controlled laboratory conditions was one of the measures to minimise this risk and enable enhanced control over the contributing parameters. Measurements were always made more than once, to reduce the effect of unknown parameters on the results. Measurements were always screened for the presence of noise and uncertainties and the conclusions were made knowing this risk or taking measures to eliminate them. When subjective tests were conducted, consistency and concordance measures were monitored to estimate the confidence level in the findings. Overall, it was tried to include wide ranges of the operational conditions in studies where time considerations allowed it, such as involving different material pairs, various input disturbances, inclusive operational conditions, and generic geometries.

Sargent [162] proposed a validation and verification plan for simulation models in design research, with defined boundaries between activities done in the real world and the simulation world. In short, the credibility of a simulation model is reflected in the degree of confidence in using a model and in the information retrieved from it. This stepwise approach was followed wherever simulation models were used in this research, to ensure the validity of the models and the credibility of the results.

5.5. POSITIONING THE RESEARCH OUTCOMES WITHIN THE FIELD

The elements included in the S&R cause-and-effect diagram, in Figure 14, have been identified through literature, field and descriptive studies. Although some of these elements and their contributions to S&R events were surveyed in previous discrete studies, an inclusive cause-and-effect diagram that gives an integrated view over the different involved factors within the engaged engineering domains in the S&R prediction was missing. Despite the discrete surveys on some of the methods and processes for the detection and severity rating of S&R sounds in a few previous publications, such as [2], [6], [10], [20], [33], [57], [64], a systematic S&R prediction process to involve different virtual and physical simulation models respecting their maturity level, methods concerning their accuracy and efficiency, and assessment measures based on the type of results was missing in the literature. By including the outcomes from the descriptive and prescriptive studies that were conducted during this PhD project, a S&R prediction framework was proposed in the form of a flowchart, as given in Figure 26. The proposed framework provides an evaluation roadmap by encompassing an array of elements in the engaged engineering domains and with a gradual evolvement in the simulation fidelity and efficiency. This framework can be used as a backbone for the S&R prediction and the sub-processes involved can be upgraded when mature methods and models are required to increase the prediction accuracy.

Concerning the studies done in the modelling and simulation domain, the following advancements were achieved. Although the role of resonance properties of the system in reducing the S&R severity was mentioned in previous works [57], [59], [65], [82], [83], a systematic method to manage the resonance risk and mode shape dissimilarity at the critical interfaces for S&R was not introduced. In study 4, a quantified method in the frequency domain was introduced to reduce the S&R risk by managing the modal properties of the parts and the resonance phenomenon. Despite the significance of geometric variation in the generation of S&R [2], [4], [6], geometric variation analysis results were passively involved in the risk evaluation of S&R events during the pre-design-freeze phases, as in the CPA analysis [4] or adjusting the clearance requirements [2], [6], [64], [129]. In study 5, a method for the active involvement of geometric variation analysis in the design phase for reducing the risk for S&R generation was proposed. This method involved an optimisation framework that was utilised in some industrial cases to apply design changes in a multi-disciplinary optimisation context, studies A1 and A4. The dependence of the stick-slip phenomenon, as the generation mechanism behind squeak sounds, on the rate weakening effect of the friction force has been shown before [6], [14], [15], [23], [25]–[27]. However, previous works on the virtual simulation of squeak events lack the sufficient involvement of friction parameters [57], [64]–[66], [86], [129], [130]. In study 1, the friction rate weakening effect was involved as an exponential friction decay coefficient in the nonlinear simulation of stick-slip events. Through empirical studies, the dependence of the friction parameters on the operational conditions was shown. As an approximation method, it was proposed to identify the relationship between the squeak severity and the operational conditions by polynomial functions. These approximations can be used to estimate the severity of squeak events from structural dynamic analysis in an efficient way. The accurate prediction of S&R events depends on the fidelity of the prediction of the contact dynamics parameters [20], [23], [89], [28], [54], [55], [57], [59], [86]–[88], which in turn demands expensive computational processes, even for small models [20], [85], [90], [91]. To address this inefficiency the application of a model order reduction approach was investigated in study 2. The effect of substructure interface definition on the accuracy of the system response was surveyed in this work.

The standard practice in the automotive industry to develop synthesised S&R excitation signals is based on the random vibration control method [68], [69], [72] despite its inadequacy in representing the time transient events [68], the increased variability in the test results [72] and the reduced prediction accuracy [74] and mainly due to the technical and practical complexities in synthesising time-history excitation signals [69]. In study 3, a method was proposed to develop efficient and inclusive S&R excitation signals in the time domain by using some statistical signal design parameters. Compared to the previous works, in which the signal trimming was based on the frequency or time-domain composition of the input signal [3], [56], [68], [69], [74], [146], and mainly the acceleration peaks, [56], [68], [69], [74], in this work, the significant parts of the reference input signal were identified respecting the severity of the system response in terms of S&R risk.

Concerning the research conducted in the assessment criteria domain, the employment of the proposed subjective listening test method in study 6 for designing a rattle sound quality metric yielded experimental data with high self-consistency and concordance levels. In contrast, the use of available subjective test methods [77], as employed in the descriptive study A2, did not produce robust results. Previous studies [10], [35], [40], [41], [43], [44], [47], [48] showed that the severity rating of S&R sounds besides their detection demands the involvement of temporal characteristics of the S&R sounds in addition to the standard psychoacoustic metrics. In this work, the statistical measure of average relative prominence was used to adjust the psychoacoustic metrics and time-dependent characteristics of impulsive sounds for a better approximation of the sound quality.

6

CONCLUSIONS

This chapter summarises the research work conducted during this PhD project and its main outcomes, as well as briefly provides an outlook for the continuation of the work.

6.1. CONCLUSIONS

As for all other product attributes, the employment of more quantified prediction approaches and verification assessment methods to treat S&R sounds has grasped the attention of automakers for some decades. However, the insufficient knowledge available about the mechanisms behind the generation and modelling of these annoying noises, in addition to the technical hurdles to efficiently integrate the identified contributors and proposed methods in the industry, have been the significant stoppers to achieving this goal. Thus, the determination of a framework to support the detection of S&R events, estimation of their severity and exploration of the causes of the phenomenon remains a necessity in the industry. The objective of this research was to address this problem by devising a framework that holds an array of activities for predicting and evaluating S&R sounds in the automotive industry. This was achieved by identifying the contributing elements to the evaluation of S&R sounds and methods to simulate their impact, further investigating and improving the elements in different domains of the framework, and demonstrating the applicability of the proposed methods in the industry. The employment of the proposed S&R prediction framework in the pre-design-freeze engineering activities can contribute to improving the final product quality without imposing the expensive end-of-line find-and-fix solutions for S&R problems. This can be achieved by providing an evaluation structure that supports the design robustness enhancement respecting the S&R risk from the early design stages.

The proposed S&R prediction framework involves prediction methods that contain elements in the three domains of system input definition, modelling and simulation and assessment criteria. The prediction activities are chained in a roadmap with a gradual increase in the method accuracy and model fidelity in three different levels. The process starts with the most efficient but less accurate evaluation methods for a fast high-level global filtration of the events. The identified risks at each level are submitted to the next prediction level that involves evaluation methods with higher accuracy and less time efficiency. The methods and tools in the prediction framework were picked from the cause-and-effect diagram that was identified through literature, field, and descriptive studies.

Below a list of the major enhancements made to the involved methods and tools in the prediction framework and the demonstrated industrial applications through the conducted studies is given.

- The utilisation of an exponential friction decay formulation to capture the rate weakening effect of the friction force showed successful and adequately accurate estimations of the squeak risk severity in the nonlinear simulation of stick-slip events for selected material pairs. From the empirical results, it was observed that the variation of friction parameters respecting the operational conditions can be represented by approximating functions to be involved in virtual simulations. It was also suggested to identify polynomial relationships between the squeak severity and the operational conditions for different material pairs to be utilised in the estimation of squeak events from linear structural dynamics results.
- The conducted studies, in agreement with the prevailing notion among the engineers regarding the virtual simulation, supports the fact that increased modelling complexity demands increased computational cost. To overcome this drawback, the application of a model order reduction method in nonlinear S&R simulation was studied. It was shown that for the sake of increased efficiency, the substructure boundaries between linear and nonlinear regions in an industrial case could be defined in the vicinity of the nonlinear regions, where S&R events happen, while the adequacy of the result accuracy was verified.

- Another approach to address the S&R simulation and evaluation time efficiency is to use inclusive but time-efficient excitation signals. A signal synthesis approach was proposed to generate inclusive but efficient S&R excitation signals in the time domain. Compared to the customary utilisation of the random vibration control approach in the industry, the proposed synthesis method can be used for different types of reference disturbances, such as stochastic, transient and frequency modulated. In an industrial case, it was shown that by a proper selection of signal design parameters effective and inclusive synthesised S&R excitation signals with adequate quality could be generated.
- Resonance properties of the subsystems are known to affect the S&R generation and severity. A systematic method to manage the resonance risk and mode shape similarity in an assembly using quantified frequency-domain metrics based on S&R severity was proposed. The application of the proposed method in design concept modification in some industrial cases proved to improve the system response respecting S&R risk.
- To actively involve the geometric variation analysis, as a major contributor to S&R problems, in the design phase of the subsystems of a car, an optimisation strategy was introduced to reduce the S&R risk. The proposed optimisation method involves a two-stage optimisation, including a decoupled initial stage to treat the risk in the rattle direction and then restraining the remaining degrees of freedom of an assembly to minimise the risk for S&R. The underlying hypothesis of the proposed method was falsified for a set of generic geometries. In some industrial applications, it was shown that the proposed method could be utilised to affordably determine the connection configuration and structural topometry in large assemblies inside the car cabin in a multi-disciplinary optimisation context.
- Until S&R virtual prediction methods would adequately replace all types of physical verifications, objective sound quality metrics are required to robustly evaluate the S&R sounds from subsystem-level or component-level physical tests. A subjective listening test method has been proposed to be used for the robust design of the S&R sound quality metrics. The method aimed at enhancing the confidence level of the subjective testing methods in eliciting the users' perception of the quality of the product. The method was used to design a rattle sound quality metric by employing new statistical measures of the psychoacoustic characteristics of the sound.

6.2. THE OUTLOOK

The presented outcomes of the PhD project in this report, involve the proposed S&R prediction framework, the enhancements made to some of the included metrics, methods and tools in the framework and their industrial applications. However, not all the contributing factors to the S&R phenomenon from the presented cause-and-effect diagram were adequately studied or included in the prediction framework. This was mainly due to the abundance of the contributing factors to the problem at hand, the diversity and broadness of the engaged domains and the resource and technical delimitations. But the author would like to restate that the proposed prediction framework can be used as the backbone for the S&R evaluation process by holding a roadmap of the S&R prediction activities. In future by the evolvement of the prediction methods and tools for involving other elements from the S&R cause-and-effect diagram, the array of methods in the prediction framework can be upgraded considering the maturity level and readiness of the tools, methods and models. A direction for future studies would be to investigate these elements to enrich the S&R prediction process. Specific suggestions for future research subjects related to the studies conducted were given in the conclusion section of the respective appended publication for each study. Here, some general directions for future work are briefly discussed.

- To increase the generalisability and robustness of the proposed metrics and methods, further descriptive studies are required to study the modelling and simulation uncertainties, especially when used for other car subsystems than the ones studied, or other applications that the automotive industry where the governing mechanisms behind the phenomena are similar to S&R events in cars, such as other types of vehicles, home appliance industries, and construction industries. These studies are required to identify the potential required method tunings, modifications, and upgrades.
- In order to support the industrial applicability and readiness of the proposed prediction framework, the parameters included in the proposed methods and metrics are needed to be fine-tuned. It is required to set engineering thresholds for the utilised quantified measures in the prediction methods and further expand the application of objective metrics in evaluating the S&R events. Furthermore, to enable and encourage the industrial application of the proposed methods, the pre-processing of the models and simulations and post-processing of the results are needed to be automated, especially by amending or embedding them into the available commercial tools.

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PAPER

Empirical characterisation of friction parameters for non-linear stick-slip simulation to predict the severity of squeak sounds

M. Bayani, A. Nasseri, V. Heszler, C. Wickman, and R. Söderberg

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PAPER II

Finite Element Model Reduction Applied to Nonlinear Impact Simulation for Squeak and Rattle Prediction

M. Bayani, A. Basheer, F. Godborg, R. Söderberg, and C. Wickman

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PAPER III

A strategy for developing an inclusive load case for verification of squeak and rattle noises in the car cabin

M. Bayani, J. Nilsson, R. Blom, C. Wickman, and R. Söderberg

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PAPER IV

Resonance risk and mode shape management in the frequency domain to prevent squeak and rattle

M. Bayani, C. Wickman, A. D. Krishnaswamy, C. Sathappan, and R. Söderberg

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PAPER V

Squeak and rattle prevention by geometric variation management using a two-stage evolutionary optimisation approach

M. Bayani, C. Wickman, L. Lindkvist, and R. Söderberg

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PAPER VI

Analysis of sound characteristics to design an annoyance metric for rattle sounds in the automotive industry

M. Bayani, C. Wickman, and R. Söderberg

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CHALMERS UNIVERSITY OF TECHNOLOGY
Gothenburg, Sweden
www.chalmers.se

The sound quality of a product conveys its operational quality. The customers - consciously or not - connect some quality attributes of a product to its sound quality, such as the powerfulness, robustness and durability. While some operational sounds in these products are designed to indicate their quality, the existence of unexpected irregular sounds in a product might be perceived as annoying if not a failure indicator. In passenger cars, squeak and rattle sounds are the most common annoying sounds of this type that are audible inside the car cabin.

For decades, customer complaints about squeak and rattle have been among the top sound quality issues in the automotive industry, burdening high warranty costs to the car manufacturers. Today, the quieter in-cabin environment due to improvements in the operational sound quality of the car subsystems, as well as the increasing popularity of electric engines, as green and quiet propulsion solutions, stress the necessity for attenuating annoying sounds like squeak and rattle more than in the past.

To rectify squeak and rattle problems in a robust, sustainable and economic way, it is needed to address the problems during the design stage of the car, where concept-related changes are economically justifiable.

This research investigates the development and application of methods and tools in different engaged fields to enable the detection and rectification of squeak and rattle risk during the car design stages.

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